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RTO AGARDograph 300
Flight Test Technique Series – Volume 27

AG-300-V27

Unique Aspects of Flight Testing Unmanned Aircraft Systems

(Aspects particuliers des essais en vol des aéronefs sans pilote)

This AGARDograph has been sponsored by the Systems Concepts and Integration Panel.

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by

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- HFM Human Factors and Medicine Panel
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- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

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RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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AGARDograph Series 160 & 300

Soon after its founding in 1952, the Advisory Group for Aerospace Research and Development (AGARD) recognized the need for a comprehensive publication on Flight Test Techniques and the associated instrumentation. Under the direction of the Flight Test Panel (later the Flight Vehicle Integration Panel, or FVP) a Flight Test Manual was published in the years 1954 to 1956. This original manual was prepared as four volumes: 1. Performance, 2. Stability and Control, 3. Instrumentation Catalog, and 4. Instrumentation Systems.

As a result of the advances in the field of flight test instrumentation, the Flight Test Instrumentation Group was formed in 1968 to update Volumes 3 and 4 of the Flight Test Manual by publication of the Flight Test Instrumentation Series, AGARDograph 160. In its published volumes AGARDograph 160 has covered recent developments in flight test instrumentation.

In 1978, it was decided that further specialist monographs should be published covering aspects of Volumes 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. In March 1981, the Flight Test Techniques Group (FTTG) was established to carry out this task and to continue the task of producing volumes in the Flight Test Instrumentation Series. The monographs of this new series (with the exception of AG237 which was separately numbered) are being published as individually numbered volumes in AGARDograph 300. In 1993, the Flight Test Techniques Group was transformed into the Flight Test Editorial Committee (FTEC), thereby better reflecting its actual status within AGARD. Fortunately, the work on volumes could continue without being affected by this change.

An Annex at the end of each volume in both the AGARDograph 160 and AGARDograph 300 series lists the volumes that have been published in the Flight Test Instrumentation Series (AG 160) and the Flight Test Techniques Series (AG 300) plus the volumes that were in preparation at that time.

Unique Aspects of Flight Testing Unmanned Aircraft Systems

(RTO-AG-300-V27)

Executive Summary

An Unmanned Aircraft System, or UAS, can range in size from a micro vehicle weighing a few pounds to a full scale aircraft weighing several thousand pounds with control systems varying from line-of-sight to completely autonomous flight profiles. Within these widely ranging bounds, UASs share a common identity as air vehicles which must be flight tested in order to be effectively and safely used in operational scenarios. Though many classic flight test techniques and considerations developed to support manned flight testing are directly applicable to UAS applications, the fact that these air vehicles are NOT MANNED demands some unique approaches to UAS flight testing and to the risk management aspects of such testing.

Since there is no person onboard a UAS during operation, some additional air vehicle risks may be accepted during flight testing given that the hazards of such tests do not directly affect personal safety. Alternatively, given that there will not be direct physical control of the UAS during testing, a means of reliable and effective flight termination must be incorporated in order to ensure that no undue risk to ground personnel occurs in the event of a loss of UAS integrity. Classic build up approaches of ground tests followed by limited flight tests and leading to full envelope operational tests can be followed with special consideration paid to test range resources and environments to maximize the effectiveness of testing while minimizing the risk.

In addition to basic air vehicle and air vehicle control system testing, UASs are of little value without effective operation of whatever airborne system they are intended to carry and support. UAS flight testing would not be complete without a thorough assessment of systems to be supported by the vehicle and should be considered unsuccessful if those systems do not work as required to meet their operational need. The small size of many UAS vehicles imposes special considerations on installed instrumentation systems and often increases the need for real time telemetry in order to efficiently analyze UAS system performance.

Future UAS applications are expanding rapidly with ever increasing improvements in vehicle performance and onboard system capabilities. UAS flight test methods and approaches must also evolve to keep pace with these advances and ensure the end user receives mature and effective UASs with known capabilities and limitations.

Aspects particuliers des essais en vol des aéronefs sans pilote

(RTO-AG-300-V27)

Synthèse

La taille d'un aéronef sans pilote (UAS), peut aller du micro appareil pesant quelques livres à l'aéronef à grande échelle pesant plusieurs milliers de livres avec des systèmes de commande variant de la commande à vue à des profils de vol totalement autonomes. A l'intérieur de ces vastes limites, les UAS partagent une identité commune, celle d'aéronefs qui doivent être testés afin d'être utilisés efficacement et en toute sécurité dans des scénarios opérationnels. Bien que de nombreuses techniques et principes des essais en vol classiques développés pour les essais avec pilote soient directement applicables aux UAS, le fait que ces appareils soient SANS PILOTE requiert une approche particulière pour les essais en vol des UAS et pour la gestion des risques liés à ces essais.

Sachant qu'il n'y a aucune personne à bord d'un UAS lors des opérations, on peut accepter des risques supplémentaires pour les appareils durant leurs essais en vol étant donné que les dangers de ces essais n'affectent pas directement la sécurité d'un individu. D'un autre côté, étant donné qu'il n'y a pas de contrôle physique direct lors des essais, un moyen de fin de vol fiable et efficace doit être incorporé pour s'assurer de l'absence de risques pour le personnel au sol dans le cas d'une perte d'intégrité de l'UAS. Les approches classiques basées sur des essais au sol suivis d'essais en vol limités et conduisant à des essais dans la totalité de l'enveloppe opérationnelle peuvent être retenues en tenant particulièrement compte des ressources de la zone d'essais et de l'environnement pour optimiser l'efficacité des essais tout en minimisant les risques.

En plus des essais de base sur l'aéronef et sur son système de contrôle, les UAS ont peu de valeur sans une utilisation efficace de tout système embarqué qu'ils sont présumés emporter et soutenir. Les essais en vol des UAS ne seraient pas complets sans une évaluation approfondie des systèmes supportés par l'appareil et seraient considérés comme insatisfaisants si ces appareils ne fonctionnaient pas comme demandé pour satisfaire les besoins opérationnels. La petite taille de nombreux UAS impose des contraintes particulières pour les systèmes d'instrumentation installés et accroît souvent le besoin en une télémétrie en temps réel pour analyser efficacement les performances du système UAS.

Les applications futures des UAS augmentent rapidement avec des améliorations toujours plus importantes des performances des appareils et des capacités des systèmes embarqués. Les méthodes et approches des essais en vol des UAS doivent aussi évoluer pour être à la hauteur de ces progrès et pour s'assurer que l'utilisateur final recevra des UAS évolués et efficaces dont les capacités et les limitations sont bien connues.

Acknowledgements

The authors would like to acknowledge the members of the SCI-172 Flight Test Technology Team (FT3) for promoting this volume and for continuing to be advocates for its publication throughout a very long development and compilation process. They would also like to acknowledge the many Unmanned Aircraft System (UAS) experts from Sweden, the United States of America, the United Kingdom, and other countries who willingly discussed their UAS experiences and offered advice and guidance on topics and UAS flight testing procedures. Finally, they wish to acknowledge the efforts of Mr. Rusty Lowry, current FT3 Chairman, for his work on final editing of this AGARDograph and his efforts to secure releasability review for this document.

Preface

It took a long time to finalize this volume as Unmanned Aircraft Systems (UAS) evolution and utilization grew more rapidly than the writing and editing of this AGARDograph could keep pace with; a situation that continues unabated to this day. Keeping in mind the rapid and continuous rate of UAS growth, the decision was made to concentrate on the basic concepts of conducting unmanned air vehicle and airborne systems flight testing rather than to capture every aspect of UAS flight testing. Hopefully, this AGARDograph achieves that goal and will help establish a basis for safe, effective, and efficient flight testing of these ever more complex aircraft.

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List of Acronyms

ACT	Aircrew Coordination Training
ADT	Air Data Terminal
ALSS	Aircrew Life Support Systems
ATC	Air Traffic Control
BIT	Built In Test
CG	Center of Gravity
CONOPS	Concept of Operations
COTS	Commercial Off The Shelf
DT	Developmental Testing
EFIS	Electronic Flight Information System
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
EMV	Electro-Magnetic Vulnerability
EO	Electro-Optical
FADEC	Full Automatic Digital Engine Control
GCS	Ground Control Station
GDT	Ground Data Terminal
GPS	Global Positioning System
HAE	High Altitude Endurance
HCI	Human Computer Interface
INS	Inertial Navigation System
IR	Infrared
JITC	Joint Interoperability Testing Command
L/D	Lift to Drag Ratio
MAE	Medium Altitude Endurance
NAD	North American Datum
NATO	North Atlantic Treaty Organisation
NATOPS	Naval Air Training and Operating Procedures Standardization
NBC	Nuclear Biological Chemical
NAVAIRSYSCOM	Naval Air Systems Command
NAVAIRINST	Naval Air Systems Command Instruction
PC	Personal Computer
PCM	Pulse Coded Modulation
POL	Petroleum Oil and Lubricants

RATO	Rocket Assisted Take Off
RCC	Range Commander's Council
RF	Radio Frequency
RPM	Revolutions Per Minute
RTCA	Radio Technical Commission for Aeronautics
SAS	Stability Augmentation System
SIT	System Integration Test
SOFT	Safety Of Flight Test
STANAG	Standardization Agreement
TECT	Test and Experimentation Coordination Team
TV	Television
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UCAS	Unmanned Combat Aircraft System
USAR	UAS Airworthiness Requirements
UTM	Universal Transverse Mercator
WGS	World Geodetic System

Chapter 1 – INTRODUCTION

While Unmanned Aircraft Systems (UASs) have seen duty with various forces around the world since the early twentieth century, the technology spurred by microprocessors in the last two decades has expanded their capability and value exponentially. The value gained by preventing the loss of human life (or prisoner of war/ hostage situations) during dangerous operations, as well as the ability to eliminate life support and egress systems has gradually exceeded the cost of integrating the required technology. In addition, this technology growth has improved reliability by allowing use of redundant and fault tolerant systems.

This document represents an effort to research and document experiences and lessons learned highlighting some of the unique aspects of flight testing unmanned air vehicle systems. It is intended to provide a practical set of guidelines in support of UAS testing from test planning and risk management through the operational suitability and effectiveness assessment. While the physical laws governing the flight of aircraft are not influenced by the presence or absence of a pilot, many of the practices developed for the collection of data from flight test events require changes in approach or new techniques when the air vehicle is unmanned. The pilot or crew is not onboard to provide qualitative data on the “feel” of the aircraft and the systems it carries. They are not on board to directly sense and provide on board mitigation of system failures. The separation of the human from the aircraft by the use of a data link is one of the key and important considerations for flight testing UASs.

An attempt is made here to provide insight on a large variety of systems to point out the differences in the testing requirements dictated by the capability of the system and the intended mission. While no all-encompassing definition has been applied to the various UASs currently fielded or under development, they are typically broken down with respect to size, operating environment, or flight control modes.

Size – The first generalized breakdown of UASs is generally related to the size of the vehicle, ranging from micro and small systems weighing less than 20 lbs to vehicles weighing as much as a manned aircraft. A small UAS, such as a Scan Eagle or Pointer typically carry fixed cameras including un-cooled infrared (IR) sensors and may carry eaves dropping, chemical/biological agent detection circuitry, or meteorological sensors. These UASs may have endurance on the order of 2 to 12 hours and are suited for missions such as surveillance, reconnaissance, and battle damage assessment. Tactical UASs are intended to support operations at the Brigade or similar sized unit level. They typically have the capability to carry 20 to 75 pound stabilized electro-optical or infrared payloads to ranges of about 100 kilometers, and provide endurance of 4 to 12 hours. In addition to the missions described for the small UAS, tactical systems may have targeting and target designating capabilities with large UAS vehicles supporting long endurance missions such as persistent surveillance and even weapons launch.

Operating Environment – Operating environments for endurance UASs are often divided into altitude bands with Medium Altitude Endurance (MAE) platforms often equivalent in size to some manned aircraft, exceeding several thousand pounds in takeoff weight. Twelve or more hours of endurance at altitude in the 15,000 to 30,000 foot range would be typical for this type of system. Large payloads and in some cases satellite data links for use beyond line of sight are also used. While electro optical (EO) payloads are frequently employed, synthetic aperture radar and moving target indicators may also be employed to support theater-wide intelligence collection. The Predator is an example of an MAE UAS. High Altitude Endurance (HAE) platforms are generally very large turbojet or turbofan air vehicles capable of extended operations above 50,000 feet, with endurance in excess of 24 hours. The very long range of these systems dictates command and control systems that have beyond line of sight capability. Missions conducted by HAE systems are both strategic and tactical in nature and may include all of the missions and payloads described in the previous paragraphs.

Both the Broad Area Maintenance Surveillance Unmanned Aircraft System (BAMS UAS) and Global Hawk are examples of an HAE UAS.

Table 1-1 shows a general layout of the groupings for UASs with the currently accepted size and operating bands displayed. Note that the size and operating bands overlap to some extent and result in at least 5 specified "Groups" of UASs.

Table 1-1: UAS Groups

	Maximum Gross Take-Off Weight (lbs)	Normal Operating Altitude (ft)	Airspeed (kts)	Representative UAS
Group 1	0-20	< 1200 AGL	< 100	Wasp III, FCS-1, TACMAV, Dragon Eye, Raven, Pointer
Group 2	21-55	< 3500 AGL	< 250	Scan Eagle, Silver Fox, Aerosonde, VCUAS
Group 3	<1320	< 18000 MSL	< 250	Shadow, Pioneer, Neptune, Mako, Tern, STUAS
Group 4	>1320	< 18000 MSL	Any	Fire Scout, Predator, Sky Warrior, FCS Class IV, Hunter, Hummingbird
Group 5	>1320	>18000 MSL	Any	Reaper, Global Hawk, BAMS, N-UCAS

Flight Control Modes – Three basic flight control modes used by UASs include rate control, stability augmentation (autopilot) control, and autonomous operations. Rate control is the most basic of control modes and provides a direct link between the input device (usually a joystick) and the position of the flight control surfaces. While this mode provides the most similarity to manned aircraft stability, control, and handling quality testing, it lacks any proportional stick force for pilot feedback. Rate control also represents the mode that requires the highest level of pilot motor skills and the associated training. For this reason, many UAS programs are avoiding use of this mode to reduce operator training costs. Rate control has been typically used in small to tactical size vehicles, but is becoming less common. Rate control can be used to operate a UAS in either the internal or external mode. During internal mode, the operator is looking at video and/or instruments in the ground control station to control the UAS, and in external mode the operator is looking at the air vehicle from outside the ground control station.

Using stability augmentation control, the operator makes discrete inputs to the autopilot outer loop (heading, altitude, or airspeed desired) and the autopilot or stability augmentation system (SAS) manipulates the flight control surfaces to achieve the desired condition. Operator inputs can be made by stick position, control knob position, or increasingly via computer interface selections. SAS or autopilot control is also referred to as vector control, and is typically operated in the internal mode, but can be used externally as well. A lower level of situational awareness and hence lower data rates may be sufficient given the increased stability.

Finally, in fully autonomous operation the air vehicle executes all flight maneuvers based on a set of instructions uploaded to the air vehicle or stored in the ground control station prior to flight. This flight control mode is typically backed up by the rate and/or autopilot flight control modes. Changes in the set of instructions (or flight plan) can often be made in flight by loading a new set of instructions, often referred to as dynamic re-tasking.

While size, operating environment, and control mode may characterize a UAS, they are not the only factors in defining test requirements, or even defining the system as a whole. System complexity is a key factor in developing a test plan and incorporating the appropriate test techniques. Factors such as data link bandwidth will help determine instrumentation requirements. Launch and recovery systems require special attention and may vary from simple rolling takeoff and landings, to systems as complex as the air vehicle itself. In summary, flight testing of UASs requires additional considerations from manned vehicle testing. This is not only due to the techniques required because there is no pilot on board, but also to the size and compound nature of the UAS. Control stations, system software, launch and recovery systems, data links, payloads, and other connected systems must all be considered in the flight testing process if a suitable and effective UAS is to be the end product.

Chapter 2 – RISK MANAGEMENT

As a precursor to flight testing, it is prudent to assess hazards and implement processes and procedures to manage risk. Processes and procedures inherent to testing of manned aircraft frequently have to be adapted to accommodate UAS technologies and capabilities, and new approaches have to be developed to address considerations unique to UASs. Four key processes used in risk management of UAS flight testing include:

1) Airworthiness/Design Assessment;

2) Configuration Control;

3) Range Clearance; and

4) Test Planning.

2.1 AIRWORTHINESS

Some type of airworthiness process using design data and/or preliminary ground/flight test data is essential to minimize the risk of inherent design flaws progressing into a flight test program. Due to the varied nature of UASs as discussed above, this process should be tailored to suit the complexity and requirements of the system. In any event, the airworthiness process or assessment should be conducted from a system perspective as technical risk may reside in control station, launch and recovery, or other systems as well as the air vehicle itself. The result of this process is generally a document referred to as an airworthiness certificate, flight clearance, or flight approval. The Flight Clearance Policy for Air Vehicles and Aircraft Systems (NAVAIRINST 13034.1C), reference [1], is the document governing U.S. Navy UAS airworthiness. The North Atlantic Treaty Organization (NATO) Flight in Non-Segregated Airspace has a draft of the UAS Airworthiness Requirements (USAR) and the RTCA SC-203 has published DO-304, dated 22 Mar 2007, that provides general UAS guidance and consideration for UASs planned to be incorporated into the National Airspace System.

Typically, the airworthiness process involves an independent review of the engineering behind the system. Qualified engineers are used to review drawings, analyses, data packages, and test data for the purpose of ensuring that proper consideration has been given to the various elements of the design, and that no errors have been introduced, and no oversight of key issues has been committed. Areas of consideration are as varied as the UASs themselves, but frequently include engineering assessments of functional areas such as; structures, performance, propulsion, electro-magnetic effects, electrical loads, software, communications, human factors, and system safety.

This process is well defined for manned aircraft and weapons systems. The unique aspect of assessing the airworthiness of a UAS is the need to tailor the process to the system. As discussed in the introduction, UASs are not easily categorized. Size, level of complexity, and mode of control combine to allow systems that span a continuum of risk. Taking an extreme case, a low cost micro or small UAS program may not have the resources to support a process that requires extensive documentation such as finite element analyses, or complex data packages. Risk management of such systems is often handled by restricting the envelope and requiring that all flights be conducted in restricted airspace over unpopulated areas. These restrictions can later be relaxed as the system matures, and demonstrates via accumulated flight hours and testing, that the appropriate level of airworthiness has been attained. Conversely, programs using a large, complex, and relatively expensive air vehicle would most likely require an airworthiness assessment essentially equivalent to that of a manned aircraft, with the obvious exception of Aircrew Life Support Systems (ALSS).

One area that deserves special attention when considering UAS airworthiness is electromagnetic compatibility. Manned aircraft with digital flight control systems also must consider, and assess this risk, but none of these are as susceptible as an unmanned system to the problems associated with this issue. The UAS relies on RF transmission of all flight control data and operator input, as well as status and system health monitoring. For this reason, ground testing with all systems operating, including engine and generator, is generally required by UAS airworthiness or flight clearance approvals. The test requires operation of all radio links in all modes to verify proper operation of all flight controls, and will be addressed in more detail in the flight testing section of this document.

A second critical consideration for UASs requiring continuous control links is how the system responds to lost communications with the ground control station. Programs vary from immediate flight termination to prevent the air vehicle from leaving the test range, to complex flight paths to attempt to reacquire the signal and navigation (avoiding terrain) to a safe field for an autonomous landing. A more detailed discussion of this subject will be included in the range safety and flight test sections.

2.2 CONFIGURATION CONTROL

While an airworthiness process as described above, is used to ensure that the design of the system is airworthy, it is essentially a useless endeavor if the configuration of the system tested does not accurately reflect the system design. In the early years of UAS testing and development, it was not unusual for the system to be handled more like a ground vehicle, or a piece of test equipment than like an aircraft. This predictably led to numerous incidents and mishaps due to attempted operations with incomplete maintenance or modifications. In order to understand and manage these risks, it is imperative that the configuration of the air vehicle and all flight critical system components, including ground elements, be maintained in a configuration consistent with that documented by the airworthiness review process. This documentation can take many forms, and is typically consistent with manned aircraft configuration control and tracking. Maintenance action forms or modification tracking sheets are typical of the documentation used. Regardless of the form taken, it is critical that any changes to the configuration be considered in light of their potential impact on the overall system. Impacts on weight and balance, flight controls, operator station displays, and navigation should be carefully considered prior to approving the new configuration for flight. With the increasing complexity, and software dependence of unmanned aviation systems, it is especially important that even minor changes to the baseline code be carefully reviewed, and that regression testing is conducted to ensure that there is no adverse impact on critical systems. Depending on system architecture, payload changes and changes to payload control software can have an impact on navigation and mission computer operation. Extensive ground testing of all flight control modes is generally required to ensure that payload software changes do not adversely impact other systems, and that the new software is ready for flight. This process need not be as intensive as the original airworthiness certification, but does require that a subset of the airworthiness process and personnel analyze and test the results of the modification prior to approval of flight operations. Again, the fact that UASs can, and do exist over the full spectrum of cost and complexity, substantiate the need to tailor their configuration product to account for the nature of the system to be tested.

2.3 RANGE CLEARANCE

The documents discussed previously in this section are intended to ensure that the system to be tested is in fact airworthy, and capable of operating over the test envelope. By contrast, the range clearance is intended as a means to protect all personnel and property in the event that a major system failure does occur. Some of the factors that impact the range safety assessment are air vehicle size/weight, speed, system complexity, hazardous

materials on board, redundancy of critical systems, and flight termination. In the United States, the Range Commanders Council (RCC) has issued a set of guidelines for UAS range safety and range clearance. The Range Safety Criteria for Unmanned Air Vehicles (RCC-323-99) is listed as reference [2]. While many of the items considered in assessing the range safety are very similar to those considered in the flight clearance, or airworthiness process, the distinction is the purpose of the assessment. It is entirely possible for a system that has been determined to be airworthy to be unacceptable for a range clearance by virtue of the fact that a failure would prevent the vehicle from being kept within range boundaries. Conversely, a vehicle or system not considered to be airworthy due to an unacceptably high probability of a flight critical failure may be an acceptable range safety risk if it employs fail-safe, or flight termination systems guaranteed to keep the vehicle in a safe area during any failure.

The critical elements of any range safety assessment will include the following:

1) Critical System Redundancy;
2) Air Vehicles Size, Weight, and Speed; and
3) Fail Safe, or Flight Termination System.

2.3.1 Critical System Redundancy

Critical System Redundancy provides a means by which the air vehicle can be safely recovered in the event of a primary system failure. Inherent with this redundancy is the need for an alert, caution, or warning system to provide the pilot/operator with notification of a failure. This provides the situational awareness needed for the pilot/operator to take appropriate action and for the range safety official to direct the planned procedure to be executed. It is important to note that there are critical systems on the ground as well as in the air vehicle. For example, it is generally required that fully redundant command and control data links be employed for UAS testing. Switching from primary to back-up command and control link may be automatic, or operator selected. Ideally, the back-up link consists of all required subsystems including the pilot/operator interface (control box), radio encoder, amplifier, and antenna system. Similarly, redundant power to the ground control station in the form of an alternating current supply, backed up by storage batteries or an uninterruptible power supply is highly desired. Back-up power supplies, both on the ground and in the air vehicle should be of sufficient capacity to provide for safe recovery from the maximum range planned for the flight. Flight control systems pose a more difficult problem on smaller air vehicles due to the size, weight, and complexity involved in fully redundant flight controls. Typically, a properly sized actuator should pose a very low failure risk. Providing a separate route to the actuator via redundant mission and navigation computers is one method that has been used. Use of a manual rate, or stability augmented manual mode, which bypasses the primary avionics, and allows access to the flight control actuators is another method. It is important to remember that the range safety assessment is considered as a whole. The above discussed measures are not necessarily hard requirements, providing that procedures or design ensure that personnel injury and property damage can be avoided despite loss of the air vehicle.

2.3.2 Air Vehicle Size, Weight, and Speed

Air Vehicle Size, Weight, and Speed provide the parameters required to analyze the distance that a disabled air vehicle will travel as well as the kinetic energy that will be imparted upon ground impact. Obviously, the ability of the vehicle to glide during some failure modes must be assessed as well. The lift to drag ratio (L/D) of the vehicle is generally used as a predictor for this case. Other factors may reduce the effective glide range to less than that dictated by the L/D ratio; for instance, the vehicle may exhibit an unstable spiral mode. In addition, any hazardous material such as fuel, batteries, and other consumables may increase the hazard area of the

vehicle. By using this data in conjunction with the fail-safe/flight termination data discussed in the following section, the range safety officials can develop a hazard pattern or "footprint" for the system. This hazard pattern can, in turn be used to develop flight routes within the test range, which ensure a minimal risk to personnel and property. One discussion that frequently develops when conducting this analysis concerns safe altitude. The obvious conclusion is that the lower the air vehicle is flown, the smaller the hazard footprint, and therefore, the safer the operation will be. This neglects the increased probability of an unnecessary mishap due to terrain avoidance workload, and the reduced reaction time available to the pilot/operator. When not dictated by test data requirements, the altitude should generally be a compromise between these conflicting issues.

2.3.3 Fail-Safe, or Flight Termination System

Fail-Safe, or Flight Termination System provides a means by which the vehicle may be maintained within range boundaries even if a failure results in a vehicle crashing. Like UASs themselves, the fail-safe and flight termination systems available run over a wide range of size, weight, and complexity. Small UASs frequently employ Commercial off the Shelf (COTS) command link encoder and decoder circuits. The majority of these devices employ a fail-safe function that allows the operator to program the controller to either maintain the last control surface position (hold mode), or set the control surfaces to a desired position (failsafe mode) if the command link is lost. In general, use of the hold mode is highly undesirable, as it could allow the vehicle to depart the range in uncontrolled flight if the failure occurs with controls neutral. The more stable the air vehicle, the more likely it will fly a long distance under these conditions. Using the fail-safe mode to set the control surfaces for level flight with power is equally undesirable. Range restrictions usually call for the throttle to be set to idle power, or engine shut down, and flight controls to glide positions. In extreme conditions, where range space is limited and risk of injury exists outside of the controlled airspace, it may be required that the controls be set to cause an immediate crash to ensure that the vehicle stays in bounds. This is often accomplished by programming pro spin control positions and engine to idle. Since the fail-safe mode can be triggered by a temporary loss of command link, it is advisable to use engine idle vice shut down, as a controlled recovery may be possible.

Larger, more complex UASs (and even many small systems) may employ an avionics package capable of at least limited autonomous control. In many cases a mission and/or navigation computer monitors the air vehicle location relative to the control station. This can be used to provide a higher level of fail-safe capability. This advanced mode may include an autonomous return if the command link is lost. This "Return Home" mode may also allow the operator to program the home destination. By choosing a destination that allows a safe ditching area, while providing close range for the command link, the operator can maximize the probability of a safe recovery while ensuring that the range boundary is not violated. The return home navigation avionics may be enabled by inputs from an Inertial Navigation System (INS), Global Positioning System (GPS), or by Dead Reckoning updates from the command link directional antenna azimuth and elevation.

The next higher form of fail-safe, and last to be discussed, is employed on more recent, and typically larger UASs. These systems are capable of significant autonomous operations including navigation and terrain clearance with no command link. As opposed to a simple return-home mode, these systems may be programmed with one or more entire emergency plans. These plans are then executed based on entry criteria including loss of command link. The plan may include recovery from the original launch site, or an abort to a recovery site closer to the air vehicle's present location. It is typical for these systems to make use of INS, GPS, and dead reckoning data with a graceful degradation to lesser modes in the event of failure(s). The emergency plan may include a climb, hold, or navigation through numerous waypoints at numerous altitudes prior to autonomous recovery. This capability can greatly improve both range and operational safety. Of course, there is an increase in cost in terms of time and money to thoroughly test all of the emergency modes in addition to the normal flight modes.

In some cases, typically when large high-speed vehicles are involved, a flight termination system completely independent of the UAS may be required. Such systems may also be required if the UAS cannot satisfy range safety requirements based on the assessment described in the previous paragraphs of this section. These systems may simply disable the air vehicle engine, cause departure from controlled flight, eject an emergency parachute, or even cause the airborne destruction of the vehicle, as in missile and rocket tests, where the speed and high volume of hazardous fuel requires such action. Flight termination systems require a high degree of reliability, and must be tested to ensure that there is no degradation of the flight termination, or UAS, due to electromagnetic effects. Any flight termination system must be proven capable of operating at a range equal to, or in excess of the maximum range planned for any flight test. These systems are employed for flight testing and generally not used once the UAS has been proven operationally suitable and reliable.

2.4 TEST PLANNING

Test plans come in all shapes and sizes. While military and some contractor test plans follow strict formats, they do vary when compared to each other. There is also variation in the test planning requirements of the individual services depending on the scope of the project. This document will focus on the portions of the test plan which deal directly with risk management or risk reduction. While it can be argued that these are not UAS specific issues, the considerations involved do vary from manned aircraft test planning. The tendency to assume greater risk to the air vehicle in light of the fact the there is no human on board to suffer injury is obvious. There are in fact cases where this is a logical conclusion. In most cases however, a disciplined approach can reduce the risk to the air vehicle and therefore the program. This is especially important as UASs continue to grow in size, complexity, and cost.

The elements of any good test plan that deal specifically with risk reduction, typically include the following:

1) Test Hazard Analysis;
2) Test Specific Emergency Procedures; and
3) Safety Check List.

2.4.1 Test Hazard Analysis

The Test Hazard Analysis is a process which seeks first to identify all hazards or risks associated with the proposed testing, then to rate those hazards in terms of both severity and probability, and then to identify means by which the hazards can be reduced. The risk remaining (residual risk) following the imposition of this risk reduction is classified into its severity and probability and is used to determine the overall test risk (risk category). This rating can then be used to drive overall test strategies such as level of review, range or airspace restrictions, or test envelope restriction. Format is much less important than content and diligence in considering the possible failure modes and their impact on flight safety. For clarity however, a sample of the format used by the United States Naval Air Systems Command (NAVAIRSYSCOM) is presented in Table 2-1 through Table 2-3. It is important to note that the Test Hazard Analysis should be based on test specific hazards. In other words, a system that has undergone extensive testing and fielding, which is undergoing new subsystem integration, would not require analysis of other subsystems that are unrelated. Conversely, testing of a prototype UAS will require an extensive Test Hazard Analysis of all safety of flight related subsystems. A failure modes analysis provided by the designers, if available, provides an excellent basis for developing such a Test Hazard Analysis. Those failure modes that pose a risk of loss of the air vehicle, injury, or property damage must be considered, and appropriate corrective action employed. Actions such as proficiency, training, and simulator runs may be used to help mitigate risks.

Table 2-1: Hazard Level Guide

Hazard Severity:	
I	Catastrophic: May cause death or aircraft loss.
II	Critical: May cause severe injury or major aircraft damage.
III	Marginal: May cause injury or minor aircraft damage.
IV	Negligible: Will not result in injury or aircraft damage.
Hazard Probability:	
A	Frequent: Likely to occur immediately or within a short period of time.
B	Probable: Probably will occur in time.
C	Occasional: May occur in time.
D	Remote: Unlikely to occur.

Applying the above guidelines to each test event provides the basis for making a risk assessment for each test event defined in the test matrix. Hazard severity levels I and II that only result in loss or major damage to the aircraft may be acceptable if the program management accepts this risk and is prepared by having several test assets or repair capability. Individual element risk categories were assigned using the risk category matrix, Table 2-1.

Table 2-2: Risk Category Matrix

Hazard Probability	Hazard Severity I Catastrophic	 II Critical	 III Marginal	 IV Negligible
A – Frequent	UA[3]	UA[3]	Category C[4]	Category B[5]
B – Probable	UA[3]	Category C[4]	Category C[4]	Category A[6]
C – Occasional	Note 1	Category C[4]	Category B[5]	Category A[6]
D – Remote	Note 2	Note 2	Category A[6]	Category A[6]

Notes:

1) The determination of a test project whose residual risk assessment falls under I/C will require up front discussions with the Test and Experiment Coordination Team (TECT) prior to proceeding with the test program development.
2) Assignment of Risk Category where residual risk falls under I/D or II/D will require up front discussions with the TECT to determine whether Risk Category A or B is applicable.
3) UA – Unacceptable risk. Project residual risk too high to proceed.
4) Risk Category C – Test or activities that present a significant risk to personnel, equipment or property, even after all precautionary/corrective actions are taken.
5) Risk Category B – Test or activities that present a greater risk to personnel, equipment or property than normal operations.
6) Risk Category A – Test or activities that presents no greater risk than normal operations.

Table 2-3: Sample Test Hazard Analysis

HAZARDOUS CONDITION	CAUSE	EFFECT	CORRECTIVE ACTION	PRECAUTIONARY MEASURE	HAZARD SEVERITY / HAZARD PROBABILITY
Loss of vehicle control / collateral damage	Autopilot Failure.	Control of UAS is lost with loss of airplane.	1) None. UAS is unrecoverable.	1) Conduct ground pre-flight checks to verify proper operation.	I/D
Loss of vehicle control / collateral damage	Data Link Failure.	Aircraft flies pre-programmed Return Home or Glide Mode with potential loss of airplane. May regain control.	1) Attempt to switch control stations. 2) RTB.	1) Conduct ground pre-flight checks to verify proper operation. 2) Monitor data link performance during flight testing. 3) Monitor instrumented parameters real-time.	II/D
Loss of vehicle control / collateral damage	EMI caused by external emitters.	Autopilot processors are disrupted, UAS control is lost with loss of airplane. May regain control.	1) Attempt to switch control stations. 2) RTB.	1) Autopilot is designed to be hardened against EMI to 200 V/m, and uses filter pins on the ADIO inputs.	II/D
Loss of vehicle control / collateral damage	Link loss immediately after takeoff with UAS at low altitude.	UAS will turn immediately toward RH point, and might not have sufficient altitude to clear airfield buildings and obstructions.	1) Attempt to switch control stations. 2) RTB.	1) Program first RH point beyond departure end of active runway into UAS to permit UAS to climb straight ahead for low-altitude RH; reprogram UAS with mission RH point once safe altitude is reached.	I/D
Failure to fly correct R/H heading in DR mode	Incorrect magnetometer heading output combined with a failure of the MC processor.	UAS will terminate return home flight at an incorrect location.	1) None.	1) Conduct ground test phase to ensure that magnetometer output is correct after alignment before proceeding to flight test.	I/D

2.4.2 Test Specific Emergency Procedures

Test specific emergency procedures must be developed in order to ensure timely response by the pilot/ operator in the event of a system failure during flight. These procedures should be developed jointly between the pilots/operators and the flight test engineers, with consideration of recommendations from the air vehicle manufacturer. In addition to documentation, the procedures should be studied, understood, and rehearsed on the ground. They should also be prepared in the form of flight cards, or Pilot Operating Handbook (Naval Air Training and Operating Procedures Standardization (NATOPS), Flight Manual ("-1"), etc.) for access during the flights. Those procedures that are most urgent should be committed to memory. These procedures are included in the test plan to ensure that proper review is included in the test plan approval process. This review process can take a number of forms, but typically a review board is preferred to a serial review. The board should consist of individuals with test experience emphasizing safety and operations. As with the Test Hazard Analysis and as implied by the name, this documentation should only address procedures required as a direct result of the system/subsystem under test. The standard flight manual for the system should cover the appropriate procedures for all other in-flight emergencies. In the case of prototype system testing, it is critical that a draft flight manual be created, and to the greatest extent possible, validated during ground testing prior to flight. This is no minor task and should be considered up front. As with the Test Hazard Analysis, a failure modes analysis generated by the design team is an invaluable document. As with all emergency procedures, immediate action items should be committed to memory.

2.4.3 Safety Checklist

The Safety Checklist, as instituted by the Naval Air Systems Command, consists of a series of standard questions for all UAS flight testing that is intended to assure that all "lessons learned", and appropriate preparations have been incorporated into the plan. The checklist is essentially a double-check of all configuration, envelope, and procedural actions implemented to minimize risk. The checklist is designed to stimulate the thinking process of all test team members so that the risks associated with all types of test operations can be materially reduced and is based on lessons learned from past mishaps. Yes and no answers are not considered adequate, but rather pointers to the location where the question's appropriate response is addressed are cited. If a question is not applicable to the test, the reason should be explained.

The larger and more complex the system under test, the more pre-test planning and analysis is needed. Mark Watson and his Global Hawk Test Team at Eglin Air Force Base expressed this philosophy in their planning stages:

> Fully autonomous systems may also require that contingency planning for various mission abort criteria be planned and pre-programmed. This planning may be based in part on the hazard analysis and serve as a mitigating factor. If the system is equipped with sufficient redundancy or fail-safe capability, it can safely recover at alternate airfields, providing the proper mission planning was done. This requires that the operators and engineers fully understand the failure mode and what limitations it places on the system. Simulation of the failures through fault insertion is invaluable in verifying the contingency or abort criteria prior to flight.

Chapter 3 – GROUND TESTING

While this document is focused on the unique aspects of UAS flight testing, experience and common sense dictate that some consideration be given to the importance of ground testing. Quality ground testing is essential not only to reduce the risk of mishap, but also to ensure that the system is technically ready for the flight testing to follow. The time and money expended on the ground is often repaid many-fold by enabling success during the typically high-visibility flight testing phase. Unfortunately, this is not always obvious when a project is successful, but a close look at failed flight tests and mishaps often indicates that the underlying problems could have easily been discovered and fixed prior to flight.

3.1 MODELING AND SIMULATION

A detailed description of several critical ground test phases will be preceded here with a brief discussion on the importance of modeling and simulation in support of UAS ground and flight test. Many current UASs, even those smaller and less expensive systems, make use of integrated avionics packages. Frequently these packages provide inertial stabilization, GPS navigation, air data computers, navigation computers, mission computers, and/or flight control computers in a single package or “black box”. This approach has led to numerous advances in cost, weight savings, reliability, and integration time savings. However, this approach can also present the tester with a difficult problem when trying to verify functionality during ground testing. Because many of the functions requiring testing and verification take place at the circuit card or even microprocessor level, it can be nearly impossible to check point to point message generation and transfer. A thorough test requires that some means of injecting all of the relevant stimuli and reading all of the relevant responses be included with such systems. This is a design issue, but must be driven by the tester if a reasonable level of confidence is to be gained prior to first flight. In older systems with analogue, non-integrated avionics and sensors, this testing was typically accomplished by “fooling or spoofing” individual sensors and examining the system response.

The same issue should be considered with respect to the control station and even the data link sub-system. The ability to force the system into a simulated flight mode with a high fidelity (preferably a six degree of freedom) model residing in the control station or avionics system (if not both), facilitates quality ground testing and improves risk reduction. It also reduces the time and effort required to find and fix problems by allowing isolation to the message containing the error.

3.2 SYSTEM INTEGRATION TEST

System Integration Testing (SIT) is a critical phase, which typically takes place in a lab environment following individual component and subsystem testing. In most cases this is the first time that all of the components and subsystems are exercised in the intended operational configuration. Historically, too little time and resources have been allocated for this effort as it is typically the last phase before formal Developmental Testing (DT) begins. Any schedule slippage that occurs during development usually results in compression of the time allotted for SIT. In addition, configuration management must be in place at the start of SIT, adding to the time required to implement the changes needed to fix the inevitable discrepancies that will be discovered. System Integration Testing is intended to find the problems not discovered in the traceability of functional requirements and Interface Control Documents used in the system design. These critical documents should be verified and corrected during the SIT. The SIT test set up should include the control station, Air Vehicle, Data Links, Launch and Recovery Systems, and any other subsystems required for the system to execute the mission. As the size of the air vehicle increases, it may not be practical to house the entire aircraft in a lab environment. In this case,

actual aircraft hardware should be utilized to the maximum extent possible (for instance, actual control surface actuators or servos can be driven by control system commands in the SIL). Subsequent aircraft-level ground testing can be accomplished to close any significant gaps remaining after SIL tests are complete.

3.3 DATA LINK AND CONTROL TRANSFER

At some point, and System Integration Testing is a good time, a thorough test of the data link system is necessary. It may be unsafe or not permissible to use the data link emitters in the laboratory environment due to hazards of electromagnetic radiation. In this case, the time and assets must be allocated to facilitate this critical test. Typically, a primary and back up data link are used. By attenuating the output power of these systems and monitoring the received signal strength, it is possible to determine whether the links will provide the range and margin determined in the design analysis. This is an absolutely critical step, known as a “range” check and should also be conducted in the intended flight test environment. It is also extremely important to verify the procedures by which the secondary (or backup) data link assumes control in the event of a primary failure. In many cases this operation is completely automatic and requires no operator intervention or action. A more difficult form of the control transfer may be required in which control of the air vehicle is transferred from one ground control station to another, rather than from the primary data link to back up data link. With less sophisticated (low cost) systems, this may be a simple matter of shutting down the data link from one station, while powering up the data link from the second station. However, even this simple process has critical training and procedural impact. In most cases, the fail-safe, or flight termination systems discussed earlier will be activated if the air vehicle receives no data link for a specified period of time. The same is usually true if the air vehicle is receiving two valid but conflicting data links simultaneously. Hence it becomes evident that operator participation, or training plan development be included in this phase of UAS ground testing. Failed control transfers have accounted for numerous UAS mishaps. The process is usually complicated by the fact that it almost always occurs over a communication radio with its own inherent complications. A basic plan for the transfer of control between two stations where the transfer is accomplished simply by switching transmitters on or off is as follows:

1) Both stations confirm they are using the same form/frequency of communication link by positive voice communication prior to initiating the transfer process.

2) Both stations confirm that essential switches and critical flight control commands including throttle setting, attitude, kill switch position, and flight control commands are on the same settings prior to initiating the transfer.

3) The receiving station declares readiness to initiate the transfer.

4) The commanding station acknowledges and declares readiness to relinquish control.

5) The receiving station initiates the transfer by giving a “standby for transfer” notice, followed by un-keying the microphone to allow the commanding station to interrupt the transfer if conditions warrant.

6) The receiving station then calls for “transfer in” and commences a countdown from 3 followed by the word “transfer”.

7) On the word “transfer” the commanding station places its transmitter to OFF, and the receiving station places its transmitter to “ON”.

8) The receiving station immediately executes some maneuver (wing rock, heading change, etc.) to verify control, and then announces successful control transfer over the radio.

This process may seem intuitively obvious, but failure to adhere to some disciplined form of coordination can have dire consequences. For instance, if step eight is not accomplished, the original commanding station operator may assume the transfer has failed and respond by turning his transmitter back on resulting in two valid links and a potential fail safe or flight termination event.

Newer, more complex ground control stations often incorporate a more automated control transfer mechanism which may eliminate the need for voice communication. Typically this will involve the air vehicle receiving a code that indicates the “address” or identity of the controlling station. When a control transfer is requested via the data link, the air vehicle avionics receives the request and relays it to any listening stations. If the commanding station acknowledges and approves of the transfer (again via the data link) the air vehicle will begin to take commands from the new station. Typically this is accomplished in a “walking transfer” technique whereby the air vehicle first acknowledges the back up transmitter of the new station, and then allows the transfer of the primary up link to the new station.

The newest generation of UASs will allow even more flexibility as the control of the payload or other subsystems may be transferred independently of the air vehicle control. In some cases the air vehicle may remain in fully autonomous flight while the control of such subsystems is transferred to the station where the data can best be exploited.

In any event, the process by which control is transferred is critical and requires extensive scrutiny during the ground test phase.

3.4 BUILT IN TEST AND AUTOMATIC TEST

Unmanned Aircraft Systems of all sizes are making more and better use of Built In Testing (BIT) and Automatic Testing. The use of these test functions increase the probability that an air vehicle brought to the flight line or launcher will, in fact, be ready for a successful launch. In addition, these functions can reduce operator workload and allow for a maintenance plan that reduces operational level tasking. Again, SIT is an excellent place for these functions to be assessed, but if not done at that time, they need to be addressed in follow-on ground testing. Typically, these tests electronically check for air vehicle response to stimuli automatically initiated at the ground control station, and for ground control station response to stimuli injected at the air vehicle. In some cases the operator may be required to intervene or stimulate the system on either end. These tests are usually referred to as inter-active tests.

In any event, the tests are only as good as the logic used to program them, and it should not be taken for granted that they will successfully diagnose all failure modes associated with the subsystems they are designed to test. In addition to the need to verify that the point to point flow of the stimulus to response is complete, it is highly desirable to inject numerous faults in order to determine which, if any are missed by the test. In some cases the BIT will simply yield a Go – No Go response. In more sophisticated systems a specific failure mode may be diagnosed and displayed to facilitate maintenance and trouble shooting. In general, the more sophisticated the BIT is, the more difficult it will be to test. A thorough understanding of the capability of the BIT or auto-test, the more likely that it will contribute to improved efficiency and ease of operation.

3.5 POWER PLANT

In general, UAS power plant testing is a more difficult task than similar testing of manned aircraft. There are a number of reasons for this. First, with the possible exception of the medium and high altitude/endurance

vehicles, regardless of the type of propulsion system employed, UASs tend to have smaller engines or motors. The small test article size places unique limits on the placement of instrumentation and monitoring equipment. Second, due to size weight and efficiency, many UASs incorporate COTS, two-stroke/cycle engines. These engines have considerably less history as aircraft power plants than four-stroke/cycle engines, and hence a much smaller database of knowledge on performance. In addition, these engines often drive propellers that are either COTS and of inconsistent quality, or are custom made with little supporting design data. Third, some small and most micro UASs are now employing electric motors in their propulsion systems for which even less data is available.

In the case of prototype air vehicle, or prototype power plant testing, it is essential, as a minimum, to verify in ground testing that the engine/motor is developing its full rated power, and that the propeller is generating adequate static thrust to permit a safe takeoff. Neither of these tasks is trivial. Fortunately, in the case of the COTS two-stroke engines, the manufacturer usually provides a specification on the rated horsepower that identifies the type of propeller used, and the revolutions per minute (RPM) produced at that rated power. These propellers are usually identified by numbers indicating the diameter and pitch. It may be necessary to ground run such engines at a lower power setting (usually attained by a fuel rich setting of a mixture control screw) to provide the recommended break-in time for the engine. Once this has been accomplished, it is a simple matter to install the specified propeller and determine whether the engine will produce the rated RPM. Most small and tactical UASs have tachometer monitoring systems, which employ Hall Effect sensors. These are usually quite accurate. The test can also be conducted with a photo-sensing tachometer, but these are generally less precise.

A note of caution: mixture adjustments with the engine running are hazardous, and the smart procedure is to shut down the engine and make adjustments between runs. Even the starting procedures (which often include an external starter manually placed against the engine hub) should be conducted with eye, ear, and hand protection in place.

Given the inconsistent quality of many of the propellers manufactured for air vehicles in the micro to tactical size, it is not at all unusual to have an engine fail to meet specified power output, and then by simply changing the propeller (same make and size), have it meet the specification. The operational impact of this is obvious, and should be considered when determining performance margins.

Once it has been verified that the engine is producing its rated power, it is also important to take at least a rudimentary look at static thrust produced by the engine/propeller combination. Again, the inconsistent characteristics of the propeller will probably require several repetitions of the test to define the performance window even if only one size propeller by one manufacturer is to be used. If a second manufacturer’s same size propeller is to be approved, the testing is doubled, as the same rated pitch from different manufacturers has proven to be entirely different, and dependent on the procedure used in design and manufacture. The test is usually conducted with a scale or load cell and a low friction dolly or carriage. Propeller performance models, such as the one presented in Numerical Method for Estimation of Propeller Efficiencies, reference [3], can be used (together with lift and drag models for the air vehicle) to determine whether performance will be adequate to proceed with flight testing. It should be noted that many such models might need to be adjusted to account for Reynolds number effects due to the small size and low speed of many UASs.

The electric motors used by some small and micro UASs are in some ways easier to test as power produced can be established by current and voltage monitoring. It is important to establish during ground testing that the power storage devices (batteries) are sufficient to provide the motor(s) with sufficient power for the required flight duration. The issues pertaining to the propellers used for these systems are similar to those discussed in the preceding paragraphs.

Turbine engines for UASs, including micro air vehicles, are becoming available. While the gas turbine (these are typically centrifugal flow compressor designs) are better understood and documented than the two stroke cycle engines, the difficulties associated with small size remain the same. Instrumentation is more difficult, and Full Authority Digital Engine Controls (FADEC) may or may not be available. In general, turbine engines for use in micro to tactical sized vehicles are considerably less efficient than larger engines. Unfortunately ground testing of range and endurance should be considered carefully before flight but is often complex and ineffective due to the efficiency improvements seen at altitude.

3.6 ATTITUDE AND NAVIGATION CONTROL GROUND TESTING

Few modern UASs operate with direct rate controls. At one time, rate control was the only mode of operation for what we referred to as Remotely Piloted Vehicles. Attitude sensing and stabilizing systems are nearly always employed, as well as some form of inertial or GPS navigation. While these systems will most likely be tested during component and SIT, it is imperative that they be exercised immediately prior to flight testing to ensure that they are operational and that their operating sense is correct.

The attitude control system may be as elementary as a single rate gyro mounted on an incline to sense both roll and yaw, and to provide basic wing leveling. Such a system combined with a barometric sensor controlling altitude can provide basic autopilot and autonomous flight functions. More often, a vertical reference gyro with a yaw rate gyro and air data computer will be used to provide position control and autonomous operations. Tactical and larger systems may employ redundant ring laser gyros and other attitude computing systems. Regardless of the component architecture, some basic safety of flight ground tests must be conducted. In cases where the design incorporates well-developed flight control laws, they can be assessed in terms of transfer functions to ensure that the correct control surface deflections result from measured attitude deviations. Ideally the vehicle is placed on a test stand to permit accurate attitude measurements. This test need not be extremely complicated however, and can usually be conducted with the vehicle on the ground. Very accurate, small, electronic angular measurement tools are available which allow alternate zero reference selection. Two such devices (calibrated) can be used to simultaneously measure air vehicle attitude in one axis and one control surface deflection. In addition, a device to stimulate the pitot-static system will be required. For a fixed wing conventional air vehicle the attitude control system test would include some or all of the following:

1) Level the air vehicle (this may require slight nose up to account for angle of attack in normal flight and wing incidence angle).
2) Supply appropriate input to the pitot-static system to drive the elevator to neutral. This will vary according to the control laws for the specific air vehicle, but typically requires providing sufficient pitot pressure to match the airspeed report to the airspeed commanded in the ground control station (GCS).
3) Raise the nose 5 degrees and check for elevator deflection trailing edge down. The amount of travel can be verified if control laws are known. Verify GCS attitude display is in agreement. Repeat in 5-degree increments until maximum allowable elevator travel is reached.
4) Lower the nose 5 degrees and check for elevator deflection trailing edge up. The amount of travel can be verified if control laws are known. Verify GCS attitude display is in agreement. Repeat in 5-degree increments until maximum allowable elevator travel is reached.
5) Roll the air vehicle 5 degrees right and check for left aileron deflection, trailing edge up (or rudder trailing edge left if rudder is used for roll axis control). The amount of travel can be verified if control laws are known. Verify GCS attitude display is in agreement. Repeat in 5-degree increments until maximum allowable aileron travel is reached.

6) Roll the air vehicle 5 degrees left and check for left aileron deflection, trailing edge down (or rudder trailing edge right if rudder is used for roll axis control). The amount of travel can be verified if control laws are known. Verify GCS attitude display is in agreement. Repeat in 5-degree increments until maximum allowable aileron travel is reached.

7) While moving the air vehicle nose left, observe yaw rate display for correct direction, and rudder (if yaw or Dutch Roll damping is implemented) for deflection right.

The airspeed and altitude deviation response should also be checked. These will be dependent on control law implementation. In many cases, the altitude sensing system (usually static pressure, or radar) will drive the throttle actuator, and the airspeed system will drive elevator. Again, by inducing a difference between commanded and reported altitude and airspeed, the correct operating sense of the elevator and throttle can be verified (elevator trailing edge down for low reported airspeed, and throttle increase for low reported altitude). With fully defined control laws, the quantitative response can also be verified. These systems will in many cases have some interaction such as long term integrators if the difference between commanded and reported data exists for an extended period.

Even without any quantitative data on control laws, these simple steps can help to ensure that the first attempt at launch or takeoff will lead to a productive data collection flight, and not a disaster. More complex air vehicle arrangements, such as V-Tails, and flying wing plan forms with elevon control can also be handled in similar fashion with a basic understanding of the control surface design. Even rotary wing air vehicles can be assessed in this fashion by measuring cyclic pitch, collective pitch, tail rotor, and power responses.

Similarly, the outer loop navigation functions need to be verified as safe for flight prior to developmental flight testing. In setting up for this ground test, a few critical steps must be taken. The GCS map display (if implemented), the air vehicle avionics, and any truth data (GPS, etc.) must all be speaking the same language. This means ensuring that these systems are all operating in the same coordinate system (UTM Grid, Latitude/ Longitude, etc.), as well as using the same mapping datum (NAD 27, WGS 84, etc.). Failure to verify these parameters will result in poor quantitative accuracy data at best, and may result in completely incorrect response to navigation commands.

Once these parameters are verified, it is possible to do some very simple ground tests to gain a significant degree of confidence in how the air vehicle will respond in flight to navigation inputs. The air vehicle can be placed on a given heading, and commanded to proceed to a waypoint to its right. The expected response for a conventional, fixed wing air vehicle is to see some right aileron deflection, trailing edge up. Knowledge of the control laws permits measurement of the surface deflection for various angles of the air vehicle relative to the commanded waypoint. This may be accomplished either by changing the waypoint, or rotating the air vehicle. Typically the controls will respond with increasing control surface deflection up to some maximum allowable angle as the heading difference is increased. Aileron deflection should be zero for waypoints on the air vehicle heading, providing the air vehicle is level, and way points to the left should result in similar left aileron deflection. Again, even without well-defined control laws to verify, this simple test can assess correct operating sense, and give the testers a qualitative feel for whether an appropriate amount of control surface deflection is induced. Any mixing of rudder deflection in this test should generally be in the same sense (coordinated turn) as the aileron deflection.

One additional and highly advisable ground test for the navigation system is to verify that the system correctly identifies that the air vehicle has arrived at a designated waypoint and executes the next step in the navigation program. If the system cannot adequately simulate this step, it can usually be accomplished by towing the air vehicle or placing it on a ground vehicle depending on size. It is valuable, but not required, to know what the

navigation software assigns as the “arrival circle” or distance from the waypoint at which it assumes it has reached the point. Convenient waypoints can then be programmed to allow the vehicle to be driven to within this radius and observed for response. The GCS displays should indicate that the waypoint has been reached, and what the new destination is. The air vehicle should respond with control surface deflection to initiate a turn toward the new point. It should also indicate altitude and airspeed response consistent with the programmed parameters. Response should be verified with new waypoints to the right and left of the air vehicle heading. Finally this test should be done while arriving at the last waypoint programmed. This step will verify the response of the air vehicle when the programmed mission is complete. It may be designed to return to base, continue on current heading, revert to some operator-controlled mode, or repeat the program. Control surface response should be verified, as well as some positive form of operator notification that the program has been completed.

Like the attitude control system ground checks, these simple steps can also be conducted on more complex air vehicle arrangements as well as rotary wing vehicles, providing the basic control response is adequately understood. If it is not, then flight testing should probably not be attempted in any event.

In general, it is possible to take a low cost system, about which little documentation is available and gain a reasonable level of confidence in the attitude and navigation control systems with some basic, inexpensive ground testing. More complex systems with well-defined control laws can benefit even more, as flight control algorithms can be verified during the process.

3.7 ELECTRO-MAGNETIC EFFECTS

Sometimes referred to as E-Cubed for Electro-Magnetic Interference (EMI), Electro-Magnetic Vulnerability (EMV), and Electro-Magnetic Compatibility (EMC), this discipline has become increasingly important in manned aircraft with the advent of digital flight control systems. With respect to UASs, electro-magnetic interference, vulnerability, and compatibility are the primary concerns due to the fact that UASs rely on Radio Frequency (RF) transmissions for all operator control inputs and all operator displays. There is no “steam gauge” or mechanical back up systems when the air vehicle may be many miles from the operator. UASs require attention to these issues in the design phase, and appropriate shielding/protection of components, actuators, wiring harnesses, and antenna cables must be built in.

Furthermore, a system that is intended to go into operational use should be extensively tested in the intended operational environment. This is usually accomplished by defining that environment, and reproducing it in a controlled or “shielded facility”. This facility must be capable of producing the desired frequencies of radiated energy, at the appropriate energy levels. For example, a system intended for shipboard use must be able to function in an environment that includes close range emissions from surface and air traffic radar systems, communications equipment, and weapons systems. Failure to do so will require that variations to normal procedures be developed, such as emissions control during UAS operations. In other words, specific systems that cause problems for the UAS must not be operated during UAS operations. This situation is not desirable and can greatly reduce the effectiveness and benefit of the UAS.

In addition to these outside sources or inter-system compatibility issues, UASs may also suffer from intra-system compatibility problems. In such cases, the problem is often related to a specific avionics or data link component, which injects RF noise into the wiring harness. The noise may then enter the data link receiver and effectively raise the noise floor, increasing the signal to noise ratio required to get a valid message received. This will reduce the effective range of the data link and may even render it unusable. It is possible for components as elementary as an updated component with a new clock oscillator to induce this failure mode. This is one of

several reasons for the emphasis on configuration control discussed in the risk reduction section of this document. The range, or attenuated signal test discussed in the data link ground test section of this document is an effective mitigation technique, providing the configuration and environment are considered.

A more thorough, but still basic EMC test should be considered mandatory before any first flight or following any configuration change. The U.S. Navy policy for this test on manned aircraft is defined in Project Test Plan Policy and Guide for Testing Air Vehicles, Air Vehicle Weapons, and Air Vehicle Installed Systems (NAVAIRINST 3960.4B), reference [4]. The procedure is called an EMC Safety Of Flight Test (SOFT). It is essentially an intra-systems test, but if conducted in the environment of the intended flight (same airfield or range) it also provides a level of comfort for system performance against any active emitters in the area. For UASs this test requires that all subsystems intended to be used during the flight be on and operating. This should include all data links, instrumentation, communications radios, and engine controls. It also requires that the air vehicle engine be running at several different RPM settings to account for ignition system noise. If the air vehicle is equipped with a generator or alternator, it must be on and operating, with any ground power or links disconnected.

The test technique requires a test engineer (with appropriate training and safety equipment) to apply manual pressure to the control surfaces as standard control checks are conducted by the pilot/operator. This process is repeated for as many different data links, transmitter powers settings, antenna types, and engine speeds as listed in the EMC SOFT plan. The engineer is looking for any uncommanded control surface or engine control fluctuations. In addition, an electrical actuator or servo, which shows a marked decrease in centering or positioning force, is often an indication of electrical noise transmitted to the device via the signal wire. This is sometimes manifested visually by the control surface overshooting the commanded position and oscillating in a lightly damped, second order system motion before assuming the commanded position. These are positive indications of an EMC problem, and flight should not be attempted until the problem is identified and remedied.

While the control surfaces are being checked, the ground control station displays are monitored for any abnormal indications, alerts, cautions, or warnings. Data link signal strength and loss of signal warnings are given extra attention. A radio frequency spectrum analyzer may also be employed during this test to ensure that all intended emitters are operating and to aid in troubleshooting if problems are encountered. Installation of additional shielding, ferrite beads, torroid coils, or other filtering are typical corrective actions once a noise source has been identified.

The EMC SOFT is planned by associating all of the flight critical systems in a source-victim matrix. This matrix is then used to execute the test and to help isolate both the source of the electro-magnetic interference, and the system being impacted (victim). A typical EMC SOFT procedure for a tactical sized UAS is presented as Annex A. A typical EMC SOFT matrix for a small UAS is presented in Table 3-1.

Table 3-1: EMC SOFT Source Victim Matrix

SOURCE → VICTIM ↓	Airborne Video System	Autopilot and Servos (1)	Downlink (All Modes)	Primary and Secondary Uplink	Test Payload	Ignition System (2)
Primary and Secondary Uplink (All Modes)	X	X	X		X	X
Downlink (All Modes)	X	X		X	X	X
Autopilot and Servos (1)	X		X	X	X	X
Airborne Video System		X	X	X	X	X

(1) Including engine controls.

(2) Engine running.

3.8 WEIGHT AND BALANCE

This issue is obviously not UAS unique, but is just as critical for longitudinal static stability as with manned aircraft. In the case of smaller air vehicles, it becomes even easier to verify, as the vehicle can typically be "hung" to verify the Center of Gravity (CG) position. It is even more critical with flying wing vehicles, as the stable range tends to be small.

An additional note is necessary here if the system is intended to use a Rocket Assisted Take Off (RATO) booster, as many UASs do. It is essential with these systems that the air vehicle be hung for all three axes, and the CG location is accurately located vertically. If not precisely matched to the design position, the forces generated by the rocket booster can easily overcome the aerodynamic forces generated by the flight controls with catastrophic results. Missing by an inch can result in the loss of the air vehicle during launch. In addition, CG travel due to fuel "slosh" may also need to be considered if the fuel can migrate due to pitch attitude or longitudinal acceleration, causing an undesirable CG shift. The effect can be checked by making CG measurements with various fuel quantities and the vehicle nose pitched up and down in flight-representative climb or descent attitudes.

In, summary, regardless of system size and complexity, a finite set of critical ground tests will go a long way to ensure a safe and successful flight test event. These tests need not be complex or time consuming and can be set up and conducted without major schedule impact. A qualitative look at power plant, data links, attitude and navigation control, Electro-Magnetic Compatibility issues, and weight and balance is imperative to reduce the risk of any first flight, or flight following a configuration change.

Chapter 4 – FLIGHT TESTING

Here we begin the discussion of actual UAS/Unmanned Combat Aircraft System (UCAS) flight test operations, and the unique challenges that are inherent in testing these systems. Reference will continue to be made to the introductory material to distinguish UAS classification, control modes, and operating scheme.

4.1 PILOTS OR OPERATORS

One can begin a heated political and philosophical discussion in some military or civil circles simply by referring to the individual controlling a UAS as a pilot! We will avoid this issue as it does little to add to the technical knowledge base for UAS flight testing. It is conceivable, however, that the men controlling shipping traffic into large ports just after the turn of the century had similar reservations about the term pilot being applied to the people experimenting with fragile flying machines.

4.1.1 Methods of Control

Regardless of the term used to identify the person (both pilot and operator will be used here), it is extremely important to look at how the task is completed and how the individual acquires the knowledge and skills required to do so. This topic once again leads us to the issues of UAS classification and flight control modes. Two primary methods of control are employed (particularly for micro to tactical sized systems), internal and external operator control.

In external operator control, the pilot controls the air vehicle while visually observing the vehicle itself and using this sight picture to interpret and control attitude and flight path. By contrast, internal operator control is conducted from inside the ground control station, by reference to telemetry data and/or real time video. The data are typically displayed as computer generated symbols similar to Electronic Flight Information Systems (EFIS) in manned aircraft. Current trends in UAS development are towards decreased use of external operator control. In fact, the trend for operational systems is toward more automation, and fewer control requirements for internal operator control as well. Some of the reasons given for the reluctance to use external pilots include:

1) Increased time required to train pilots to interpret and control attitude and flight path from visual cues.
2) The redundancy of requiring both types of pilots since the external pilot cannot be used for down range operations.
3) Historically higher mishap rates during external operations of systems that use external pilots for launch and recovery.
4) The need for additional GCS equipment (external flight control boxes, etc.).

These points are, in general, valid for operational UASs. However, the point can also be made that for developmental testing of micro to tactical size UASs, the external pilot can be a very valuable asset. The following arguments can be used to address each of the reasons for reluctance to use external pilots:

1) Increased pilot training time is true. Anecdotal evidence indicates that taking a group of twelve individuals with no training or experience and putting them through a syllabus typically produces up to six qualified internal pilots, but probably no more than two qualified external pilots. However, it is also certainly true that training a test pilot takes considerably more time and effort, and has a higher failure rate than training an operational pilot.

2) Pilot redundancy assumes there is no value added by this second form of operation. Again, probably true for operations, but not necessarily for flight testing.

3) There are higher mishap rates using external pilots, but there are several reasons for this trend. Typically, systems employing an external pilot (such as the U.S. Navy Pioneer) use the pilot primarily for the high pilot workload tasks of takeoff and landing, or launch and recovery. Night operations and recovery into a net on a moving (not to mention pitching, heaving and rolling) ship are routine, and it is not hard to understand the challenge to accomplish this without mishap.

4) The requirement for additional equipment can be justified for developmental testing by interfacing a COTS control box with the ground data link terminal.

4.1.2 Qualifications

Some additional historical background is also in order here. As UAS development and testing has progressed for the past two decades, both government and contractors have typically recruited external pilots from the ranks of the aero-modeling community. This is a logical course of action, because the skills required to control the air vehicle from the external perspective have already been developed in these individuals. These skills are usually developed with aircraft that operate exclusively in the rate control mode, with no stability augmentation. Therefore, these pilots have the ability to recover air vehicles (assuming reasonable static stability) even in the case of autopilot or other catastrophic failures by reverting to direct rate control of the flight control surfaces. This is not typically the case for internal pilots.

The problem is that these skills are necessary, but not sufficient for UAS flight test operations. The missing knowledge and skills required for flight testing must be developed by additional training and experience. Furthermore, it may not be possible to develop these skills in all candidates. The primary requirement is system knowledge. The average aero-modeler does not need to know and understand the myriad of subsystems and reversionary modes available on most UASs. This is absolutely imperative for flight test operations. In addition, an engineering background is essential. The pilot must understand the data being collected if he is to perform the test in an efficient manner. Finally, the pilot’s training must develop the flight test discipline that all flight test programs require. Go – No Go decision making, proper briefing, and test coordination must all be included in the external test pilot’s training.

Similarly, internal pilots or operators need to have the training and experience to maintain a very high state of situational awareness. Operational employment varies between countries and even individual services. U.S. Navy UAS pilots are generally enlisted ranks, while the Air Force typically uses rated flying officers. Status, class, and rank are of little impact, but training and experience are even more critical for flight test than for operational employment. Again, training or experiences in an engineering discipline, or even graduation from a test pilot school, are highly desirable, if not required traits.

For both internal and external pilots, a training, qualification, and currency plan should be employed. As with manned aviation, the essential skills deteriorate with lack of use. Air Traffic Control (ATC) coordination, weather, and Aircrew Coordination Training (ACT) are typical of manned aircraft training subjects that should be included in the UAS test pilot training syllabus.

4.1.3 Feedback

A fundamental and unique aspect of UAS operation is the complete lack of the multitude of subtle cues provided to the pilot of a manned aircraft. Wind noise, engine vibration, peripheral cues, and feel of acceleration on the

human body are all missing for the UAS pilot. The safe operation of a UAS requires intense concentration on exclusively visual feedback (audio systems are now being implemented on some systems). The ability of the human brain and vision system to adapt and manage this environment should be the subject of another entire paper! A frequent topic of discussion among UAS pilots is how two different air vehicles, or two different flight envelopes can "feel" completely different, despite being controlled by the same pilot interface, with the same or no, force feedback. This phenomenon appears to be entirely a learned effect, based on visual cues and knowledge of the vehicle or conditions. While much of this discussion is based on experience with small or tactical sized UASs, similar comments can be seen in technical reports and literature such as The X-36 Program: A Test Pilot's Perspective on UAV Development Testing, reference [5], the subject of which is the X-36 high performance sub-scale air vehicle.

4.2 COMMAND AND CONTROL

Command and control constitutes the single largest difference in UAS flight testing as compared to manned aircraft testing. It can be generalized that most UASs contain at least four basic command and control components:

1) **Ground Control Station (GCS)** – The GCS may or may not be contained within a shelter or container. It is the focal point from which all operator commands are sent, and all air vehicle reports are displayed. Emphasis will be placed on the operator interface and its relation to concepts of operation.

2) **Ground Data Terminal (GDT)** – The GDT generally contains the radio link ground based transmitter(s), and receiver(s). As discussed earlier, it is normal for most UASs to have at least two data links for redundancy. In addition to this primary and backup link architecture, the links are bi-directional and usually referred to in terms of the Up Link, or command link, and the Down Link, which may also be referred to as the telemetry link. Many systems also incorporate a third data link, which is also technically a down link, but is used exclusively to carry the payload video or other sensor data. Other systems have the telemetry data imbedded on the same link. Some systems also now incorporate satellite data links.

3) **Air Data Terminal (ADT)** – The ADT provides the same function as the GDT without the displays, but is located in the air vehicle. For this reason, it must obviously be smaller, consume less power, and be of lighter weight. It has direct and indirect interfaces with the flight control computers.

4) **Antenna System** – The antennas are connected to the GDT and ADT via hardwire or fiber-optic cable. These systems can range from simple dipole omni-directional radiators, to state of the art, high gain arrays. Directional systems may be steered via GPS data provided by the GDT and GCS, signal strength tracking, or manual tracking.

4.2.1 Ground Control Station

The types of systems employed and concept of operations are extremely varied, and will be addressed in general terms according to historical precedent and current trends.

The most basic command and control operator interface employed in the developmental testing of small and even tactical UASs, like the first generation of UAS pilots, was adopted from the aero-modeling community. High-end, COTS radio control systems and components have been adapted for use on numerous UASs. These systems offer an extremely low cost way to facilitate human interface with command and control and incorporate excellent reliability with a wide range of very useful features. The use of these COTS systems as they exist is extremely risky and in most cases illegal. The transmitters used in most such system operate on

frequencies that are established for aero-modeling (72 Mega-Hertz in the United States), and are generally not approved for government use. In addition, the power output from the transmitters is typically on the order of 300 milliwatts, which is insufficient for flight beyond visual range. Boosting this signal with RF amplifiers is again unwise, and not legal. The command and control link for any UAS must be on a frequency, and of a bandwidth approved by the frequency coordination authority. Use of these civil frequencies not only subjects the UAS command link to potential interference, but boosting the signal has liability issues for damage to privately owned model aircraft over a large area.

This is not to say that these components can not be used. In fact, many small UAS projects have successfully used the COTS interface and saved substantial investments in engineering and design. The RF section of many of the Pulse Coded Modulation (PCM) transmitters is modular and can be removed. Similarly, with the receiver crystal oscillator removed, the receiver decoder can be employed in the air vehicle. The serial data from the control box can then be fed into an appropriate, approved data link transmitter. The data link receiver in the air vehicle can then feed the data into the COTS receiver for decoding and it may even be used for driving COTS servos.

Several words of caution are appropriate here. In addition to disabling any RF functions in the COTS transmitter and receiver, it is important to provide power to the servos from a clean regulated power supply or battery. Voltage drops at the COTS receiver may activate built in warning systems, which may have adverse impacts on the flight control system. Another consideration is that these COTS control boxes have become extremely sophisticated as micro-processor technology has “computerized” the radio control systems. A thorough understanding of the functionality, which varies with manufacturer and model, is critical. Switches that can reverse servo direction, change gain, or mix channels are typical. Inadvertent operation of these functions can be disastrous.

As UASs increase in cost and complexity, custom designed pilot interface controls are more likely to be employed. Many systems are now being designed to use Human Computer Interface (HCI) displays and controls with no pilot box or joystick hardware. This type of interface is generally used with air vehicles implementing primarily autonomous flight modes, with the operator supplying “outer loop” (i.e. altitude, airspeed, and heading) inputs through the HCI.

Thorough GCS testing is, in general, a fairly laborious task. During the System Integration Test phase, individual messages to and from the GCS must be verified. The Ground tests discussed previously can be used to verify most of the flight critical functionality. Additional testing must include a human factors assessment. The issues that need to be addressed are:

1) Is flight critical data displayed in easily readable locations and easily interpreted displays?

2) Is the interface for pilot input (joystick, control box, mouse, etc.) intuitive to operate, and responsive?

3) Is the situational awareness provided by navigation and attitude displays, including map displays if implemented, adequate for precise positioning of the air vehicle with respect to the mission requirement?

4) Are appropriate cautions, warnings, and alerts displayed and do they support rapid completion of the emergency procedures they are designed to trigger?

5) System latency will be discussed further, and is typically more likely to be generated by the data link than the GCS, but if it is suspected to be a problem, it should be measured through the GCS to help identify the major contributing subsystems.

6) Finally, some assessment of pilot workload should be conducted for both normal and emergency procedures. Cooper-Harper handling qualities, Bedford workload, or some similar structured analysis should be employed for this assessment. Annexes B and C provide sample formats.

Most Ground Control Stations incorporate a second workstation or “Bay” which is used by a payload operator. The tests described for the pilot’s controls and displays are “in general” appropriate for the payload controls and displays as well.

4.2.2 Ground Data Terminal

The testing of the ground data terminal is normally a straightforward process. Message traffic into the terminal usually follows a well-defined format. It is often an industry standard format such as RS-422. The verification of the data traffic may require some test equipment to decode and display the messages. These tests can be complicated by contractor proprietary data formats, so it is advisable to include contractor support during ground and/or SIT testing to decode and assess the data in such cases.

Transmitter and encoder/decoder testing can also be accomplished with basic radio-communications test equipment. Receiver sensitivity, transmitter power output, and spectrum analysis for on-frequency transmission are typical tests. The test results should be compared to design analysis of the GDT performance.

4.2.3 Air Data Terminal

Air data terminal testing is essentially similar to the GDT testing described above. Decoding and interface with the flight control system may require additional attention.

4.2.4 Antenna Systems

Antenna system testing is also straightforward in most cases. The complexity of the system may vary, but essentially the frequency and power radiated, and the reflected power should be assessed. Some systems may provide automatic testing and display of this data. Obviously, satellite communications systems will have their own test and validation requirements.

Directional antenna systems may be steered by components that are part of the antenna system, and may also rely on some GDT components. Range and azimuth calibration tests are generally required if the system tracks on signal strength. GPS steered systems can be tested by varying the air vehicle position or GDT position inputs and observing the response. If omni-directional back up systems are used, the switching between the two systems should also be tested.

Operational employment frequently calls for the antenna system to be placed 400 to 500 meters from the GCS for tactical reasons. If the communication line to the antenna system is hard wired, the system should be tested to verify sufficient signal drive to overcome the line impedance. If fiber-optic cable is used, it should be assessed for resistance to damage by foot traffic or other expected disturbances, to ensure operational suitability.

4.2.5 Latency

As automation and computerization of UASs increases, assessment of end-to-end system latency becomes very critical. As mentioned before, satellite data links now employed by some systems have raised this issue to an even higher level. The round trip time for these links can exceed several seconds. Additionally, the use of Local Area Networks, and wireless networks within the command and controls systems can add additional

delays dependent on switching and request traffic. The benefit to such systems is the ability to distribute information and control to where it can most effectively be employed. Obviously, the impact of latency on air vehicle operation is directly related to the degree of automation, or the requirement for direct control.

Surprisingly, preliminary results from tests at the Naval Air Warfare Center Manned Flight Simulator as, presented in reference [6], indicate that using direct, stick control (position and rate modes) UAS pilots were able to adapt well to increased latency. Both internal and external pilots performed tasks such as accurate landing with latencies that would be unacceptable in manned aircraft. This data is not conclusive, and the trend is toward using automated launch and recovery systems with the operator essentially handling “outer loop” control assignments to the air vehicle autopilot during flight.

When testing systems with high latency, another consideration is payload utility. The classic UAS task of surveillance may require manual manipulation of camera pointing. Can the operator locate and point at the target without numerous overshoots due to the delay between the camera direction and the displayed video? This too, may be dealt with by employing automation such as point to coordinate, auto search, and auto track. These functions must be tested to ensure operational suitability, and to assess operator workload. Similarly, UCAS brings the issue of weapons systems control. The system must be tested to determine if weapon release authority can be safely determined and executed with delays in the indication of target status.

The trend toward increased air vehicle autonomy has many potential pitfalls for the tester. In addition to isolating the pilot from air vehicle response in a general sense, it can prevent corrective action during flight-safety critical events. The presence of excessive latency in the data or video can lead to pilot induced oscillation in the internal mode, which then forces a requirement for sufficient data link bandwidth to mitigate the problem. The desire for increased autonomy is certainly achievable for operational systems. However, in the flight test environment it is this author’s opinion that reversionary flight control modes, up to and including direct rate control in some cases, are highly desirable. Several large UAS system mishaps and many smaller ones, which have occurred during developmental test flights, almost certainly could have been avoided by such reversionary or panic modes. It falls back to the need for highly trained and experienced UAS test pilots/operators to make use of these capabilities. Large sophisticated UAS and UCAS systems are typically very software intensive and highly automated. In many development programs, the software code generation is spread over a large number of very competent and highly skilled programmers. It is not uncommon, despite the best systems engineering processes to have issues with the integrated package during flight testing. Furthermore, the flight test environment is not well understood by those on the outside, and is frequently not adequately considered as the code is developed based on operational requirements. At some point, the desire to reduce the flying skills required by the operator of the system in the field, leads to automation which essentially relegates the flight test team (including the pilot) to the status of spectators during the flight. This situation should be considered during the risk mitigation steps discussed previously. If it is possible for a flight mode to fail, which leaves no option for the pilot other than flight termination, modification of the system for flight testing should be considered. Flight control modes, such as emergency modes, that can not be exited once entered should raise a warning flag. Modifications to system hardware and software to facilitate the extra control modes can be removed once suitable maturity and system safety have been demonstrated. If they are never actually needed then the cost of the program may have been slightly inflated, but if they are needed and work just once, they may save the entire program.

4.3 INSTRUMENTATION

UAS system testing presents both unique challenges and opportunities in the area of flight test instrumentation. In the case on micro to tactical sized systems, the combined limitations of payload size and data link bandwidth

may preclude the addition of any new down linked data parameters. On the other hand, many such systems already pass a multitude of data, which can be picked up at the GDT using a Personal Computer (PC) to record the data. The data can often be played back via the GCS or the PC and displayed for analysis. In addition, it may be possible to display critical parameters including engine power settings real time during high-risk flight tests to facilitate monitoring by flight test engineers.

In cases where the data required is not available on the data link or truth data is required, but the air vehicle can not support the installation of additional instrumentation, several innovative approaches have been developed. Live video down links, intended for payload or the pilot’s view intended for vehicle operation by the operator have been used to bring down data either by encoding on the video or audio channels, or by pointing the camera at small data displays or instruments on the air vehicle. This technique has included placing small compass in the corner of the camera field of view, and adding attitude reference lines to the video display monitor. A method for facilitating navigation system performance data in situations where there is no payload available to install a radar-tracking beacon, or the beacon presents an Electro-Magnetic Interference hazard, chaff has been used to supplement the radar signature. By spreading chaff of the appropriate length for the radar frequency band thinly on wide pieces of tape, and placing the tape flush on the exterior of the air vehicle, solid radar “skin paint” tracks can be generated. This procedure requires a range radar system of sufficient accuracy and resolution to provide accurate truth data from the track.

If instrumentation, telemetry transmitters, and/or radar beacons are installed for testing, it is imperative that they be installed and operating during the previously described EMC Safety of Flight Test. A list of critical parameters to be instrumented must be constructed for each test that balances data requirements against weight, cost, bandwidth, and other instrumentation issues. Some parameters may include engine power response and requirements, sensor electrical drain, flight control displacements, and such along with common items such as altitude, airspeed, and heading.

4.4 AIR VEHICLE FLYING QUALITIES

Flying qualities represents another unique aspect of UAS/UCAS flight testing. At first glance, there would appear to be little logic in even addressing the issue. If you consider traditional measurements, such as stick force per g, they seem to have no value. If the pilot has a stick at all, it will have the same force at 600 knots and 10 g’s as it has with the air vehicle in the hangar! Specifically it will be equal to a spring constant times the amount of stick deflection. Yet, as mentioned in the previous discussion on pilots/operators, it is a fact that there is a discernable difference in most cases between the “feel” of an air vehicle that is stable and controllable and one which behaves poorly in either respect. This is especially true of systems with rate control, but can be discernable even in less direct control modes. This is not to say that flying qualities testing is always necessary, or even appropriate. If the system is essentially autonomous, with little direct operator input other than altitude, airspeed and heading commands submitted with a mouse click, then there is probably little to be gained. If the reversionary modes discussed in the previous section are incorporated, they should probably be evaluated to ensure some level of comfort if needed. This may actually be done via simulator if the simulation is of sufficient quality, and the flight test poses high risk.

In the case of a UAS with a rate control mode, and stick control (pilot control box) some interesting techniques have been employed. The BQM-147A is a small delta wing unmanned aircraft (UA). During testing for a jammer payload mission, a flying qualities assessment was conducted. As detailed in Flying qualities and Performance Evaluation of the BQM-147A with a Simulated Communications Jammer, reference [7], the payload limit was insufficient for instrumentation, but the side area of the upper fixed,

and lower retractable antennae warranted an assessment of the flying qualities impact. By carefully calibrating the incidence angles of the forward-looking video camera, and applying a measured angular overlay to the video monitor, the horizon and fixed ground references were used to quantify pitch, roll, and yaw excursions. Using basic manned aircraft flying qualities techniques, the longitudinal and lateral-directional characteristics of the system were analyzed. The resulting data was in direct agreement with the qualitative assessment of several pilots familiar with the handling qualities of the air vehicle. Selected tables, figures and results from the reference technical report are included as Annex D.

At the other end of the spectrum, several large UASs have been successful using alternative acquisition strategies, which essentially only test the system mission capabilities. These are highly automated vehicles and control stations with satellite links. Any test of the flying qualities of this type of system, would essentially be a test of the autopilot algorithm response to operator requests for changes to the flight path.

4.5 AIR VEHICLE PERFORMANCE

Like flying qualities, there is a large variation in the need for and utility of performance data collection. In all cases, the system will have specific performance requirements and specifications. In many cases however, the performance being measured is that of the system and may have little to do with the capability of the air vehicle-power plant combination. For instance, if the specification is for the system to be capable of achieving a 1,000 foot per minute climb rate under given atmospheric conditions, it is a simple matter to request an altitude change at the GCS and determine if the vehicle achieves and maintains the specified climb rate. The traditional methods, such as saw-tooth climbs and level accelerations would be of little use, because the system would limit the performance to the value programmed for conditions. For instance, if maximum airspeed is commanded from some much lower speed, the system is likely to use only 80 percent of rated horsepower or thrust, and then roll that in via an integrator circuit or algorithm over 5 or 10 second period. Thus, the acceleration is not what the vehicle can perform, but what the autopilot/GCS will allow. On more complex vehicles, it may be feasible to incorporate flight test modes in the control laws to permit an operator to override the auto control schedules, providing the capability to perform maneuvers such as maximum power accelerations or climbs.

Critical performance issues for UASs in traditional missions are more likely to be parameters like range, endurance, and time on station for a given profile. Testing for these specifications is fairly straight-forward. One parameter that should be assessed in detail is takeoff or launch performance. It is very important to collect sufficient data to accurately assess system performance at high density altitudes. Even autonomous launch modes will normally use maximum available power or thrust for takeoff, so if performance is anemic under normal conditions, the impact on operational performance in adverse conditions like high, hot and humid locations should be analyzed and reported.

The advent of UCAS systems with air-to-air capability will undoubtedly change this approach to air vehicle performance testing. In an environment where maximum sustained and instantaneous turn rates, speed, and acceleration are critical, these parameters will have to be tested, and the envelope expanded to its maximum potential. This may be conducted with man-in-the-loop, or by “canned” maneuvers.

One advantage of UASs for both flying qualities and performance testing is the ability to inject precise maneuver commands from the ground control station. This technique has also been used for recovery system integration, where pitch frequency sweeps of specific magnitude and frequency were required for response analysis. The air vehicle response can be captured by the same PC injecting the commands, which facilitate an automated analysis and fast turn around.

4.6 SYSTEM FLIGHT TESTING

The bulk of UASs flight testing, beyond the subjects already addressed, involves payload testing. The variety of payloads employed on UASs continues to grow and is beyond the scope of this document. Some of the most common payload types will be addressed here.

4.6.1 Electro Optical

Electro Optical systems are by far the most common UAS payload. Essentially a combination of daylight television (TV) and IR, the system is used for a variety of missions including; surveillance, reconnaissance, battle damage assessment, and targeting. These payloads have demonstrated significant operational utility. In some cases, the IR payload and the daylight TV payload may be separate units carried interchangeably, but not together. In either case, the testing is quite similar with respect to the payload capability. The sensitivity and resolution of both types of sensors are tested and analyzed the same as they would be tested on a manned aircraft. The sensor sensitivity (minimum resolvable temperature difference for an IR sensor, or minimum resolvable contrast for a visible EO sensor) and resolution (spatial frequency) are measured under various conditions as detailed in reference [8], the U.S. Naval Test Pilot School Flight Test Manual: Systems Testing (USNTPS-FTM-NO. 109). EO sensitivity and resolution testing should be conducted in both static (ground) and dynamic (in flight) environments using resolution grids.

The most essential outcome of any assessment is the overall accuracy of the system. By definition, the accuracy of any system is no better than the accuracy of the system(s) that provide information to it. A series of assessments are required if the intent is to improve the targeting accuracy:

1) First, the navigation accuracy of the UAS must be precise because it is typically the basis for the remaining targeting calculations. Earlier UASs relied primarily on GDT tracking in range and azimuth (ρ,θ) for air vehicle location. These systems require a very accurate survey of the GDT location to provide reasonable accuracy. Newer systems generally use P-Code GPS data or differential GPS for air vehicle position data.

2) Next, the air vehicle altitude, attitude and heading must be precisely resolved. Typically this needs to be better than one tenth of a degree in all three axes for good results. Some payloads may provide this data independently, but that is typically not the case. GPS altitude is typically not sufficient for good results due to satellite geometry with respect to the vertical axis.

3) The payload pointing angles relative to the air vehicle must now be resolved with a high degree of accuracy.

4) Finally, the target altitude must be supplied. This can be done by comparing the target location to a terrain elevation database, or by providing slant range via laser or other range finding device.

In addition to accuracy, the update rate of these data to the targeting computer (which may be air or ground based) must be sufficient relative to air vehicle speed. A 1 Hertz update at 120 knots can yield a 200-foot (approximately 66-meter) error in the base calculation.

4.6.2 Communications Relay

Communications relay payloads are frequently employed to provide extended range, or over the horizon data transmission from other systems. Flight testing of these systems requires special attention to frequency coordination and EMC issues. Typically, integration of these payloads will require additional shielding, and/or

employment of band pass filtering. It is important to test the UAS system on all available command and control frequencies. Most UASs have at least some frequency agility, and failure to test all combinations of up and down link frequencies can result in major problems in operational employment.

4.6.3 Jammers

Jamming payloads are employed to deprive adversaries of normal communication and data transmission channels. Obviously, all of the comments listed in the previous paragraph apply to jammer payloads to an even greater degree. Intra-system effects such as the jammer signal entering the wiring harness and disrupting air vehicle sensors is not unusual. Testing of these systems, once successfully integrated, is usually centered on the effectiveness of the payload against the intended victim sources. This will often involve flying specific profiles at various ranges to document effects of range and attitude on effectiveness.

4.6.4 Nuclear, Biological, and Chemical Detectors

Nuclear, Biological, and Chemical Detectors (NBC) sensors can vary from very small (less than 1 pound) units that must be visually checked, up to 40 pound systems which can down link specific data on agent types and concentrations. Developmental testing usually starts by focusing on integration with existing telemetry streams, or addition of payload specific links. The systems must then be tested for functionality that often involves the use of agent simulants to trigger detection. Some detectors will require flight profiles that place the air vehicle in the simulant cloud, while others can detect from stand off positions. In the case of nuclear or radiological testing, RF emissions are generally used to simulate the field, and the air vehicle/payload is used to map the concentrations. Attention to hazardous materials safety is critical during the planning and execution of the flight testing of these systems.

4.6.5 Emulation

Emulation packages may be used to "spoof" sensors into identifying the UAS as another aircraft or even surface vehicle. It is possible for these systems to be essentially passive, existing essentially of various energy reflectors. More often, they will have RF emitters as well, and require attention to EMC issues as with the relay and jammer packages described above. Flight test profiles will also most likely require illumination with various threat detection systems to quantify the effectiveness of the payload.

4.6.6 Lethal Payloads

Integration of lethal payloads is a requirement for UCAS systems. Air-to-Air and Air-to-Ground weapons may be integrated and tested. Classic manned aircraft approaches to weapon separation and weapon system testing will be required. In addition, the issue of weapon release consent must be considered. If the system is largely autonomous, or has large latency, the employment of the weapon may have to be automatic. This is not all that dissimilar from cruise and standoff weapon testing. It will be critical for the UAS and weapons test communities to work closely and exchange test technique information to conduct safe and effective testing of these systems.

4.6.7 Launch and Recovery Systems

Many tactical and smaller UASs incorporate zero-length or short takeoff assist launching systems. These systems require attention to structural issues and may require additional ground testing to verify both, structural integrity, and avionics survivability in this harsh environment. Longitudinal load factors up to 25 g

are not unusual. The issue of pilot intervention during initial flight testing is also an important consideration. By definition, the air vehicle will be at low altitude and airspeed during the test, and reaction to any anomaly must be swift and correct. Initial tests from elevated positions may be desirable to improve the available response time. As mentioned earlier, the relationship of the air vehicle center-of-gravity (in all axes) to that of the launch system must be accurately established in ground testing.

Similarly, recovery systems employing nets, or tail hook arrested landings induce additional structural ground test and/or analysis. Again, the low altitude and airspeed normally associated with these tests require a method of intervention that is quick and correct. Some recovery systems incorporate ground and airborne transponders to provide autonomous glide path control. Others accomplish this task using differential GPS and radar altimeters. All of these subsystem components need to be tested prior to integrated system testing. Automated wave-off programs have been used successfully in place of operator intervention. The complexities imposed by environmental conditions (density altitude, wind, etc.) must be thoroughly documented and accounted for. When ship motion is added to the equation, the need for extensive modeling and simulation of the recovery system, prior to flight, becomes apparent.

4.7 OPERATIONAL SUITABILITY

The issues that need to be addressed for operational suitability of a UAS/UCAS system are generally not unlike those normally considered for manned aircraft. Where applicable, some of the critical points have been addressed in previous sections. One complicating factor is the myriad Concepts of Operation (CONOPS) that have been introduced for UAS fielding. The frequent use of accelerated acquisition processes, and COTS equipment, require additional consideration during developmental testing. Some issues to consider include:

1) Will the COTS software package or operating system be supported by the time the system is fielded?
2) Has the COTS hardware received sufficient environmental testing (particularly if shipboard operations are planned) to ensure survival in the intended environment?
3) Does the CONOPS preclude field (Operational Level) maintenance, and is this reasonable given DT experience with maintenance issues/problems?
4) Is planned operator and maintainer training sufficient to support the system based on DT experience?
5) Will the tested air vehicle envelope support operations in the CONOPS planned environments (hot, cold, high density altitude, etc.)?
6) Was the EMC testing conducted during the developmental tests consistent with the expected environment specified by the CONOPS? Communication center and shipboard RF environments are intense and system should be tested against them prior to fielding.

Additionally, many UASs still require gasoline and two-stroke oil. These are no longer a part of many military Petroleum, Oil, and Lubricants (POL) logistics support plans. A plan must be in place to provide logistical support for any of these required materials. Similarly, back up batteries may be difficult to support due to hazardous materials issues, or the lack of recharging facilities. Electrical requirements must be consistent with the sources available within the unit structure defined by the CONOPS.

4.8 INTEROPERABILITY

The utility of any UAS system is limited if the data collected by its sensors, and the control of targets to be prosecuted is “stove piped”. Military systems intended to meet Joint Services needs are required to meet

interoperability standards in order to ensure that they can provide mission data that can be used by used by any of the forces involved in a campaign. The Joint Interoperability Testing Command (JITC) is responsible for setting and verifying these standards.

Similarly, at an International level, standards are necessary to ensure that NATO countries can control and exploit the product provided by UASs. To this end, NATO Standardization Agreement (STANAG) 4586, reference [9], has been developed. This agreement details the processes and interfaces required to provide for command and control as well as data exploitation for various legacy and developmental UASs operated by NATO countries.

Chapter 5 – REFERENCES

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[5] Purifoy, D., *The X-36 Program: A Test Pilot's Perspective on UAV Developmental Testing*. Dryden Flight Research Center Document Number DRC-97-55, June 1999.

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Annex A – TYPICAL TACTICAL CLASS EMC SOFT PROCEDURE

Buno ______ C-Band ___GHz UHF ___MHz S-Band ___ GHz

A.1 TEST GROUP GROUND POWER

1) Apply ground power to air vehicle with battery installed.
2) Configure GCS for payload installed.
3) Confirm RF communication with the UA (both links, low power omni).
4) Confirm IFF Transponder emitting.
5) Run UA Automatic test. Test System ON and OFF. Note all failures.
6) Verify all UA warning lights are extinguished.
7) Select all UAS TX to low power.
8) Select all GCS TX to low power.

A.2 AIRCRAFT POWER – ENGINE RUNNING

1) Start UA engine.
2) Verify engine idle 3200-3500 RPM select A/V Power.
3) Verify RF communication on all links, Test System ON.
4) Verify UA control checks under the following conditions:
   a) C-band secure commanding – low power.
   b) C-band clear commanding – low power.
   c) UHF commanding – low power.
5) Command >5000 RPM.
6) Verify UA control checks under the following conditions:
   a) C-band secure commanding.
   b) C-band clear commanding.
   c) UHF commanding.

7) Command RPM to idle.

8) Select all UA TX to high power.

9) Select all GCS TX to high power.

10) Verify all UA warning lights are extinguished.

11) Select all UA TX to low power.

12) Select all GCS TX to low power.

13) Repeat 3 through 14 with Test System OFF.

14) Configure UA for engine shut down.

15) Secure Engine.

16) Secure UA Power.

No anomalies were noted other than the autotest steps with Test System OFF. Control surfaces in all transmit and receive modes with Test System OFF or ON operated smoothly with consistent force and positioning. No oscillation or hunting was observed in any mode.

Annex B – COOPER-HARPER RATING SCALES

<table>
<tr><th colspan="3">Pilot Decisions</th><th>Aircraft Characteristics</th><th>Demands on Pilot in Selected Task or Required Operation</th><th>Rating</th></tr>
<tr><td rowspan="6">Is satisfactory without improvement?</td><td colspan="2" rowspan="3">Yes</td><td>Excellent, highly desirable.</td><td>Pilot compensation not a factor for desired performance.</td><td>1</td></tr>
<tr><td>Good, negligible deficiencies.</td><td>Pilot compensation not a factor for desired performance.</td><td>2</td></tr>
<tr><td>Fair, some mildly unpleasant.</td><td>Minimal pilot compensation required for desired performance.</td><td>3</td></tr>
<tr><td rowspan="3">No</td><td rowspan="3">Deficiencies warrant improvement.</td><td>Minor but annoying deficiencies.</td><td>Desired performance requires moderate pilot compensation.</td><td>4</td></tr>
<tr><td>Moderately objectionable.</td><td>Adequate performance requires considerable pilot compensation.</td><td>5</td></tr>
<tr><td>Very objectionable but tolerable deficiencies.</td><td>Adequate performance requires extreme pilot compensation.</td><td>6</td></tr>
<tr><td>Yes</td><td colspan="5"></td></tr>
<tr><td rowspan="3">Is adequate performance attainable without a tolerable pilot workload?</td><td rowspan="3">No</td><td rowspan="3">Deficiencies require improvement.</td><td rowspan="3">Major deficiencies.</td><td>Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question.</td><td>7</td></tr>
<tr><td>Considerable pilot compensation is required for control.</td><td>8</td></tr>
<tr><td>Intense pilot compensation is required for control.</td><td>9</td></tr>
<tr><td>Yes</td><td colspan="5"></td></tr>
<tr><td>Is it controllable?</td><td>No</td><td>Improvement mandatory.</td><td>Major deficiencies.</td><td>Control will be lost during some portion of required operation.</td><td>10</td></tr>
</table>

Figure B-1: Cooper-Harper.

<table>
<tr><th colspan="3">Operator Decisions</th><th>Difficulty</th><th>Operator Demand Level</th><th>Rating</th></tr>
<tr><td rowspan="6">Is mental workload level acceptable?</td><td colspan="2" rowspan="3">Yes</td><td>Very easy, highly desirable.</td><td>Operator mental effort is minimal and desired performance is easily attainable.</td><td>1</td></tr>
<tr><td>Easy, desirable.</td><td>Operator mental effort is low and desired performance is attainable.</td><td>2</td></tr>
<tr><td>Fair, mild difficulty.</td><td>Acceptable operator mental effort is required to attain adequate system performance.</td><td>3</td></tr>
<tr><td rowspan="3">No</td><td rowspan="3">Mental workload is high and should be reduced.</td><td>Minor, but annoying difficulty.</td><td>Moderately high operator mental effort is required to attain adequate system performance.</td><td>4</td></tr>
<tr><td>Moderately objectionable difficulty.</td><td>High operator mental effort is required to attain adequate system performance.</td><td>5</td></tr>
<tr><td>Very objectionable but tolerable difficulty.</td><td>Maximum operator mental effort is required to attain adequate system performance.</td><td>6</td></tr>
<tr><td>Yes</td><td colspan="5"></td></tr>
<tr><td rowspan="3">Are errors small and inconsequential?</td><td rowspan="3">No</td><td rowspan="3">Major deficiencies, system redesign is strongly recommended.</td><td rowspan="3">Major difficulty.</td><td>Maximum operator mental effort is required to bring errors to moderate level.</td><td>7</td></tr>
<tr><td>Maximum operator mental effort is required to avoid large or numerous errors.</td><td>8</td></tr>
<tr><td>Intense operator mental effort is required to accomplish task, but frequent or numerous errors persist.</td><td>9</td></tr>
<tr><td>Yes</td><td colspan="5"></td></tr>
<tr><td>Even though errors may be large or frequent, can instructed task be accomplished most of the time?</td><td>No</td><td>Major deficiencies, system redesign is mandatory.</td><td>Impossible.</td><td>Instructed task cannot be accomplished reliably.</td><td>10</td></tr>
</table>

Figure B-2: Modified Cooper-Harper.

Annex C – BEDFORD WORKLOAD SCALE

Decision Tree		Workload Description	Rating
Was workload satisfactory without reduction?	Yes	Workload insignificant.	1
		Workload low.	2
		Enough spare capacity for all desirable additional tasks.	3
	No	Insufficient spare capacity for easy attention to additional tasks.	4
		Reduced spare capacity. Additional tasks cannot be given the desired amount of attention.	5
		Little spare capacity. Level of effort allows little attention to additional tasks.	6
Yes			
Was workload tolerable for the task?	No	Very little spare capacity, but maintenance of effort in the primary task not in question.	7
		Very high workload with almost no spare capacity. Difficulty in maintaining level of effort.	8
		Extremely high workload. No spare capacity. Serious doubts as to ability to maintain level of effort.	9
Yes			
Was it possible to complete the task?	No	Task abandoned. Pilot unable to apply sufficient effort.	10

Figure C-1: Bedford Workload Scale.

Annex D – EXCERPT FROM SA-5R-92

INTRODUCTION

BACKGROUND

1. The Marine Corps has an operational requirement for a small, expendable remotely piloted vehicle (RPV) to transport an electronic communications jammer to a predesignated target area. EXDRONE, an RPV formerly known as EXJAM 80, was developed in 1981 by the Johns Hopkins University Applied Physics Laboratory in response to the Marine Corps requirement. This unmanned air vehicle (UAV) is intended to satisfy the requirements of lower level tactical units and small ships for a capability to investigate local area activities. The UAV Joint Program Office has placed EXDRONE in a special category called Very Low Cost UAV. EXDRONE has been modified to carry a global positioning system (GPS) navigation receiver and VHF communication jammer payload to support the Marine Air Group Task Force Commander by providing a low cost, highly effective alternative to ground-based communication jamming systems. EXDRONE has been officially designated as the BQM-147A.

2. NAVAIRWARCENACDIV Patuxent River, MD, was tasked by reference 1 to integrate and test a GPS navigation system and a VHF communication jammer package for the BQM-147A vehicle and validate the system through ground and flight testing. The flying qualities and performance (FQ&P) tests were conducted at the Naval Electronic Systems Engineering Activity between 11 July 1991 and 18 March 1992.

PURPOSE

3. The purpose of this test program was to evaluate the effect of the jammer package on the FQ&P of the vehicle and assess the suitability of the vehicle for the expendable jammer and training missions.

DESCRIPTION OF TEST AIRCRAFT AND EQUIPMENT

4. The BQM-147A was a low cost, remotely piloted, expendable drone. The vehicle was a delta planform flying wing with drooped leading edge anhedral wingtip extensions. These extensions were intended to enhance the low speed flying qualities of the vehicle. Directional stability was provided by a single vertical stabilizer mounted centrally on top of the trailing edge of the wing. Control moments were provided by separate elevators and ailerons mounted on the trailing edge of the wing, and a rudder mounted on the vertical stabilizer. The vehicle was powered by a one cylinder, two cycle, air cooled engine capable of producing approximately 7 bhp. A three-view drawing of the test vehicle is presented in appendix B, figure 1.

5. The flight control system consisted of an uplink receiver connected to an autopilot and electrical servo motors that actuated the flight control surfaces and throttle via push/pull rods. The autopilot provided essential flight reference information, and varying degrees of vehicle flight control assistance. The autopilot allowed the vehicle to be flown either manually, with the assistance of a wing leveler, or fully autonomously.

6. For the purpose of this test, a simulated jammer package was installed in the test vehicle. This package consisted of a fixed 3 ft antenna mounted on top of the fuselage about midway between the nose and tail, an electrically retractable 3 ft antenna mounted under the fuselage directly beneath the upper antenna, and an internal weight to simulate the mass of the electronic components. The locations of the antennas are indicated in appendix B, figure 1.

7. The only instrumentation parameters available from the vehicle were engine RPM, barometric altitude, and heading. These parameters were not sufficient for the flying qualities testing that also required at least a rough idea of the vehicle's pitch and roll angles, as well as the rates about all three axes. The data were derived by placing an overlay with pitch and roll markings over the video screen. A copy of this overlay is presented in appendix B, figure 2. A hand-held stopwatch was used to time the relevant vehicle motions.

SCOPE OF TESTS

8. NAVAIRWARCENACDIV Patuxent River completed a total of six FQ&P test flights (4.9 flight-hours) of the BQM-147A test vehicle with a simulated jammer package installed. These tests were conducted at or below 1,200 ft MSL with ambient temperatures between 85°F and 90°F for the first five flights, and approximately 40°F for the final flight. Flying qualities of the vehicle and antenna structural integrity were evaluated at a cruise power setting of 6,000 RPM with the lower antenna retracted and extended, and at full power with the lower antenna retracted. The flight test configuration matrix is presented in appendix C, table I. The flight test accomplishment matrix is presented in appendix C, table II. The proposed straight line speed runs and stall tests were not completed due to funding and time constraints.

METHOD OF TESTS

9. The structural integrity of the antennas was evaluated by observing their ability to withstand the forces imposed on them during the FQ&P testing. The power setting was, however, limited to a cruise setting when the lower antenna was extended, since this antenna was not designed to be extended during the high-speed dash portion of the mission profile.

10. The flying qualities of the BQM-147A vehicle were evaluated using variations of the flying qualities test techniques for manned aircraft which are described in reference 2. It was possible to use the standard manned aircraft techniques in most cases because most of the flying qualities testing was conducted from the internal pilot station using the onboard video for reference. Details of the specific techniques used are contained in the FQ&P matrix of appendix C, table II. The major exceptions to the use of standard manned aircraft techniques were takeoff and landing. These operations are normally performed by the external pilot whose only references are the visual appearance of the vehicle and the sound of the engine. It was very difficult to define meaningful, measurable tasks for these operations. Consequently, the evaluation of the takeoff and landing flying qualities was based solely on the subjective opinion of the external pilot.

11. Two mission relatable tasks were used in conjunction with the Cooper-Harper handling qualities rating scale to help evaluate the lateral/directional characteristics. The Cooper-Harper scale is presented in appendix A. The tasks used were a bank angle capture task and a heading capture task. The tasks were performed in rudder-only and aileron-only turns. The tolerances for the tasks were defined as ±2 deg desired and ±5 deg acceptable for both tasks.

RESULTS AND DISCUSSION

ANTENNA STRUCTURAL INTEGRITY

12. The structural integrity of the jammer antennas was evaluated over the full operational envelope of the vehicle from takeoff to maximum level flight speed for the upper antenna, and takeoff to the 6,000 RPM level flight speed for the lower antenna. The first upper antenna to be tested exhibited severe oscillations throughout the entire speed range and failed within 10 min of takeoff. The second upper antenna remained intact throughout the remainder of the flights and showed only minor vibration at very high speeds. No problems were observed with the structural integrity of the lower antenna. The failure of the first antenna proved to be due to a manufacturing defect that should not be seen in the production antennas. Since the good upper antenna and the lower antenna both lasted for more than four flights, their strength will be more than adequate for the expendable jammer mission that will require only one flight per vehicle. Within the scope of this test, the structural integrity of the current antenna design is satisfactory for the expendable jammer mission.

TAKEOFF AND LANDING FLYING QUALITIES AND PERFORMANCE

TAKEOFF

13. The takeoff tests were conducted from a smooth hard-surfaced taxiway near sea level with light winds and ambient temperatures between 85°F and 90°F. Initially, the bungee was stretched to 100 ft. This resulted in the vehicle rolling 15 to 20 ft past the bungee stakes before lifting from the dolly. An increase in bungee stretch to 105 ft resulted in a liftoff point closer to the end of the bungee stroke. In all cases, the climbout was shallow, but the vehicle was stable and responded positively to the controls. With the exception of the shallow climb, this takeoff performance was similar to the BQM-147A vehicle's performance without the jammer package. The extra weight of the simulated jammer package, and the presence of the antennas will not adversely impact the ability to launch the BQM-147A, provided the 105 ft bungee stretch is used. Within the scope of this test, the takeoff performance and flying qualities of the BQM-147A vehicle with simulated jammer package and antennas are satisfactory for safely launching the vehicle on expendable jammer and training missions.

LANDING

14. The landing tests were conducted on a smooth hard-surfaced taxiway near sea level with light winds and ambient temperatures between 85°F and 90°F. The landing speed appeared to be higher than the nonjammer version of the BQM-147A vehicle due to the additional weight. However, the pilot did not have difficulty landing on or maintaining the centerline of the landing surface. The vehicle did not show any tendency to depart from controlled flight at approach and landing speeds. The extra weight of the jammer package and the presence of the antennas will not adversely impact the ability to safely recover the vehicle on training missions. Within the scope of this test, the landing performance and flying qualities of the BQM-147A vehicle with simulated jammer package and antennas are satisfactory for safely recovering the vehicle during training missions.

UP AND AWAY FLYING QUALITIES

LONGITUDINAL FLYING QUALITIES

Static Stability

15. An attempt was made to quantify the static stability with the vehicle trimmed at 6,000 RPM with the lower antenna retracted. Additionally, the static stability was evaluated qualitatively throughout the test series. Qualitatively, the vehicle exhibited positive static stability in all configurations throughout the tested flight envelope. No differences were noticed between the antenna extended and antenna retracted configurations. The quantitative results are presented in table I. The results of the quantitative test were difficult to apply in a conventional manner due to the coarseness of the RPM measurement (60 RPM increments), and the difficulty of relating RPM to airspeed. However, the test results did tend to corroborate the qualitative observation of positive static stability. The positive longitudinal static stability will assist in making the vehicle easier to handle under manual control during jammer and training missions. Within the scope of this test, the longitudinal static stability of the BQM-147A vehicle is satisfactory for the expendable jammer and training missions.

Table I

LONGITUDINAL STATIC STABILITY AT 6,000 RPM

Stick Position	Engine RPM
1/16 in. forward	6,000
neutral	6,000
1/16 in. aft	5,880
1/8 in. aft	5,760

Dynamic Stability and Control

Response to Longitudinal Stick Inputs

16. The response to longitudinal stick inputs was tested at 6,000 RPM with the lower antenna retracted and extended and at full throttle with the antenna retracted. Sinusoidal stick pumping was used to identify the short period damped natural frequency. Pitch doublets were used to estimate the short period damping ratio. The results from the stick pumping and pitch doublets are presented in table II. No difference was noted between the characteristics with the antenna extended or retracted. No overshoots were observed after the pitch doublets, thus indicating a highly damped condition for all tested configurations. The damped natural frequency was quite high at cruise power settings with an even higher frequency at high power settings. The high natural frequency coupled with the heavy damping made precise control of the pitch attitude exceptionally easy. This combination of responses to longitudinal control inputs will make the vehicle easy to handle in pitch under manual control and in both steady and maneuvering flight. This will reduce the required skill level and minimize the training requirements for BQM-147A operators. The BQM-147A vehicle's rapid and well damped response to longitudinal stick inputs is an enhancing characteristic that should be incorporated in future RPV designs.

Table II

SHORT PERIOD CHARACTERISTICS

Power Setting	Antenna Position	Damped Natural Frequency (sec^{-1})	Damping Ratio
6,000 RPM	Retracted	4.8	> 0.7
6,000 RPM	Extended	4.8	> 0.7
Max	Retracted	6.3	> 0.7

Phugoid Mode

17. The phugoid mode was evaluated at 6,000 RPM with the lower antenna both retracted and extended, and at full throttle with the antenna retracted. The test was performed by pulling the nose of the vehicle approximately 10 deg above the horizon to slow the airspeed, then releasing the stick. Data were obtained by counting the number of pitch overshoots and measuring the time taken for the nose to move away from the horizon and back again. This allowed the calculation of the phugoid period and approximate damping ratio. The data from these tests are presented in table III. The data indicate that power setting has a significant effect on the phugoid period, since the period is doubled by going from 6,000 RPM to full throttle. This is probably more of an airspeed effect than a power effect, and it would be expected since the period of the phugoid mode is generally proportional to the airspeed. Power did not, however, effect the damping, since both antenna retracted points exhibited a heavily damped phugoid with only two overshoots. Antenna position had no effect on the period, but did have a significant effect on the damping. When the antenna was retracted, the phugoid mode was heavily damped. However, extension of the lower antenna yielded an essentially undamped phugoid mode. The maneuver had to be terminated due to airspace constraints after approximately five overshoots with no apparent reduction in amplitude. This reduced damping also showed up as difficulty in precisely trimming the vehicle in pitch. With the lower antenna extended, the vehicle exhibited a constant tendency to drift up or down regardless of the position of the trim lever. This tendency was a minor annoyance, but could be easily controlled as long as the pilot paid attention to his altitude. Additionally, this trimming difficulty did not appear to significantly impact the performance of the autopilot during the limited autopilot testing that was completed. Even though the undamped phugoid mode with the lower antenna extended is a minor annoyance while under manual control, it will not have a significant adverse impact on the ability of the BQM-147A vehicle to accomplish the expendable jammer or training missions. Within the scope of this test, the phugoid mode of the BQM-147A vehicle is satisfactory for the expendable jammer and training missions.

Table III

PHUGOID CHARACTERISTICS

Power Setting	Antenna Position	Period (sec)	Damping Ratio
6,000 RPM	Retracted	19	0.5
6,000 RPM	Extended	20	0.0
Max	Retracted	40	0.5

LATERAL/DIRECTIONAL FLYING QUALITIES

Static Stability and Control

18. The lateral/directional static stability and control characteristics were evaluated during steady heading sideslips at full throttle with the lower antenna retracted, and at 6,000 RPM with the lower antenna extended. Flat turns were also attempted at 6,000 RPM with the antenna retracted and extended, since the antenna patterns might necessitate the use of flat turns while the jammer was in operation. No significant differences were noticed between the two steady heading sideslip configurations. Both configurations displayed a slight positive dihedral effect in that one half and full rudder required approximately one quarter and one half opposite lateral stick, respectively, in order to hold a steady heading. The positive dihedral effect was also demonstrated through the ability to control bank angle during rudder-only turns. No significant differences were noticed between left and right sideslips. A very slight sideforce was also observed through the necessity to maintain approximately a 5 deg bank angle to hold a steady heading with full rudder. However, this sideforce was not enough to allow flat turns to be executed. The slight yaw rate generated with the wings held level was too small to be practical. Though the inability to perform flat turns was initially a concern, the actual antenna patterns revealed that flat turns will not be necessary for the expendable jammer mission. Consequently, the lateral/directional static stability and control characteristics will not adversely affect the ability of the BQM-147A vehicle to perform the expendable jammer or training missions. Within the scope of this test, the lateral/directional static stability and control characteristics of the BQM-147A vehicle are satisfactory for the expendable jammer and training missions.

Dynamic Stability and Control

Roll Mode

19. The roll mode characteristics were evaluated at 6,000 RPM with the antenna retracted and extended using a bank-to-bank roll technique. This technique involved starting from a 20 deg bank angle, establishing a steady-state roll rate, and releasing the stick as the bank angle passed through zero. The time to go from the stick release to zero roll rate was then recorded and used to calculate the roll mode time constant. A qualitative evaluation of the roll mode was also made using a bank angle capture task during aileron-only turns at 6,000 RPM with the antenna retracted and extended, and at full throttle with the antenna retracted. Quantitatively, the roll mode time constant was too short to measure with hand-held instrumentation. It is estimated to be less than 0.1 sec. This short time constant gave the vehicle a quick and well damped response to lateral stick inputs. Bank angle capture tasks were easy at all power settings both to the left and to the right. The bank angle capture task was slightly easier to accomplish with the antenna extended (HQR 2) than it was with the antenna retracted (HQR 3). The maximum roll rate was not evaluated quantitatively; however, the internal pilot did not feel the need to use full lateral stick at any time during the test flights. Therefore, the maximum roll rate was judged to be more than adequate. The crisp and well damped roll response will make the vehicle easy to control in roll for the manual portions of the expendable jammer and training missions. Within the scope of this test, the roll mode response of the BQM-147A vehicle is satisfactory for the expendable jammer and training missions.

Spiral Mode

20. The spiral mode characteristics were evaluated from left and right 20 deg banked turns at 6,000 RPM with the lower antenna extended and retracted, and at full throttle with the antenna retracted. The 6,000 RPM point with the antenna extended was also completed with the wing leveler on. The test results are presented in table IV. These data indicate that the vehicle was unstable to the left and stable or neutral to the right. This result was verified by the necessity to hold some top aileron or rudder in stabilized left turns. It was also slightly more stable at higher

power settings, and had longer time constants with the lower antenna extended. The longer time constants could be due to either greater rolling moment of inertia or higher roll damping. Engaging the wing leveler had the desired effect of stabilizing the spiral mode, both to the left and to the right. The difference in times between the two different techniques indicated a lack of absolute aileron centering; however, this had no significant effect on the flying qualities. In all cases, the spiral stability was sufficient to allow the pilot to control the vehicle without undue attention to the bank angle. The current spiral mode characteristics will allow the BQM-147A vehicle to be flown with confidence on both expendable jammer and training missions. Within the scope of this test, the spiral mode characteristics of the BQM-147A vehicle are satisfactory for the expendable jammer and training missions.

Table IV

SPIRAL MODE CHARACTERISTICS

Power Setting	Antenna Position	Wing Leveler	Time (left turn) (sec)		Time (right turn) (sec)	
			Control Into[1]	Control Away[2]	Control Into	Control Away
6,000 RPM	Retracted	Off	4.3[3]	5.6[3]	> 20[5]	4.5[4]
6,000 RPM	Extended	Off	7.3[3]	7.8[3]	> 20[5]	> 20[5]
6,000 RPM	Extended	On	4.6[4]	—	4.9[4]	—
Maximum	Retracted	Off	6.8[3]	7.0[3]	> 20[5]	3.8[4]

NOTES: (1) Controls released into turn.
(2) Controls released away from turn.
(3) Time to double amplitude.
(4) Time to one half amplitude.
(5) Angle of bank did not change perceptibly for more than 20 sec.

Dutch Roll Mode (Wing Leveler Off)

21. The Dutch roll mode was evaluated at 6,000 RPM with the lower antenna extended and retracted, and at full throttle with the antenna retracted. This evaluation was accomplished using directional frequency sweeps to determine the natural frequency, and rudder doublets to determine the roll to yaw and damping ratios. The quantitative results are presented in table V. A further qualitative evaluation of the Dutch roll mode effects on mission tasks was accomplished using bank angle and heading capture tasks during aileron-only and rudder-only turns. The qualitative data from the mission tasks are presented in appendix C, table III. The Dutch roll was characterized by a fairly fast, very lightly damped (7 to 9 overshoots) snaking motion. The damping was slightly higher at high power settings, but it was still very low, displaying about 7 overshoots. A slight frequency increase was noted for high-power settings and low-power settings with the antenna extended. This could be explained by the greater fin effectiveness in the high energy prop wash, and the lower yawing moment of inertia with the extended antenna. The Dutch roll characteristics did not seriously affect the bank angle capture tasks because of the low roll to yaw ratio (HQR 2-3). The heading capture task, however, was very difficult due to excitation of the Dutch roll mode (HQR 4-6). The motion was easily excited by any aileron or rudder inputs and atmospheric turbulence, but could be damped by careful use of ailerons or rudder. The ease with which the Dutch roll was excited led to an almost constant yaw oscillation that made it impossible to get a stable video image if any maneuvering was being conducted. The vehicle did, however, remain under full control and was fairly easy to navigate. External control of the vehicle was not significantly impacted by the lightly damped Dutch roll. Consequently, the lightly damped Dutch

roll will not seriously affect the ability of the operator to control the vehicle during training or expendable jammer missions since these missions do not require accurate nose pointing or tracking. However, the lightly damped Dutch roll may seriously degrade the quality of the video imagery if the vehicle is to be used for reconnaissance missions. Within the scope of this test, the Dutch roll characteristics of the BQM-147A vehicle are satisfactory for the expendable jammer and training missions. Further testing involving tracking of ground targets is recommended for the reconnaissance version of the BQM-147A to ascertain whether the lightly damped Dutch roll will adversely affect the quality of video imagery, especially in turbulent atmospheric conditions.

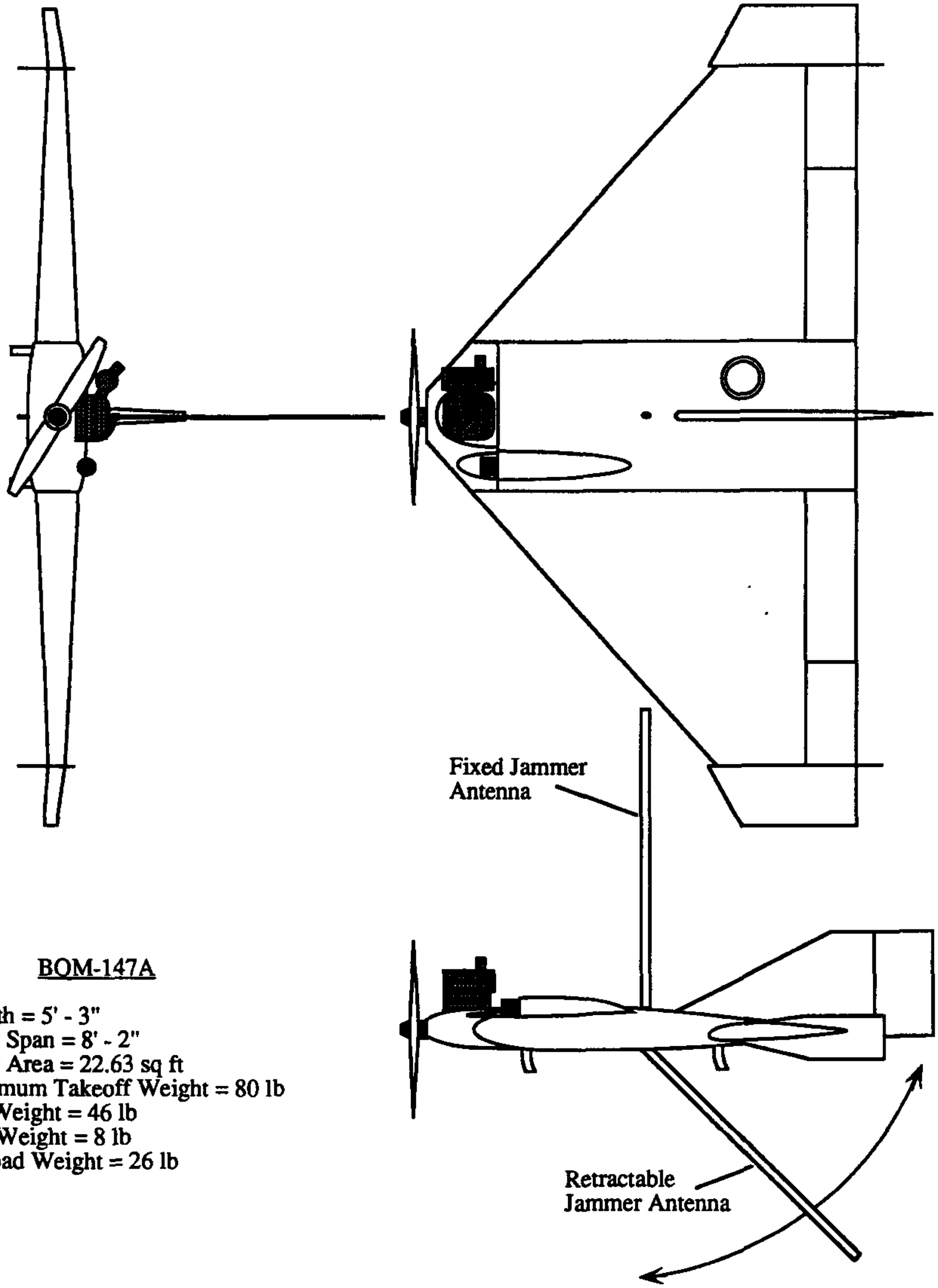
Table V

QUANTITATIVE DUTCH ROLL CHARACTERISTICS

Power Setting	Antenna Position	Damped Natural Frequency (sec^{-1})	Damping Ratio	Roll-to-Yaw Ratio
6,000 RPM	Retracted	2.7	< 0.1	Very Low
6,000 RPM	Extended	3.9	< 0.1	Very Low
Maximum	Retracted	3.9	0.1	Very Low

Dutch Roll/Wing Leveler Interaction

22. The wing leveler function of the autopilot was evaluated during aileron-only turns at 6,000 RPM with the lower antenna extended. A later qualitative evaluation was also conducted after the incorporation of a yaw damper in the wing leveler control laws. Upon engagement of the wing leveler, in its initial configuration, the vehicle began to oscillate in roll and yaw with a roll-to-yaw ratio somewhat greater than the Dutch roll, but at approximately the same frequency. The oscillations built up to an apparent limit cycle with a maximum roll of approximately ±20 deg. All attempts to damp the oscillations with lateral stick inputs resulted in increased amplitudes. Rudder could be used to successfully damp the oscillation, however, phasing of the inputs was critical. If the phasing was not absolutely correct, the amplitude would increase. Attempts at bank angle capture tasks revealed that if all oscillations were completely damped out before the maneuver, the actual task of capturing the desired angle was fairly easy (HQR 3), but the bank angle could not be maintained for more than a few seconds, as the oscillation would build up quickly to a limit cycle. If some small oscillations (±5 deg AOB) were present at the start of the maneuver, the desired bank angle was very difficult to capture (HQR 7), and the magnitude of the oscillations continued to build until the turn had to be aborted. The oscillations did not appear to have reached any kind of limit cycle by the time the turn was aborted. The heading capture task could only be accomplished very roughly, in a completely open loop sense, by releasing the controls. Any attempt to actively capture a heading resulted in increasing roll/yaw oscillations. After the incorporation of the yaw damper, heading and bank angle capture tasks were both easy. Even aggressive control inputs resulted in a maximum of two roll overshoots with very little movement in yaw. The most significant impact of the final version of the wing leveler was a dramatic decrease in the roll control effectiveness. This tends to decrease the maneuverability of the vehicle; however, it would not significantly effect the expendable jammer or training missions. Use of the wing leveler/yaw damper combination will significantly reduce the pilot workload during expendable jammer and training missions. Within the scope of this test the performance of the wing leveler in conjunction with the yaw damper is satisfactory for the expendable jammer and training missions.



BQM-147A

Length = 5' - 3"
Wing Span = 8' - 2"
Wing Area = 22.63 sq ft
Maximum Takeoff Weight = 80 lb
Dry Weight = 46 lb
Fuel Weight = 8 lb
Payload Weight = 26 lb

Figure 1
THREE-VIEW DRAWING

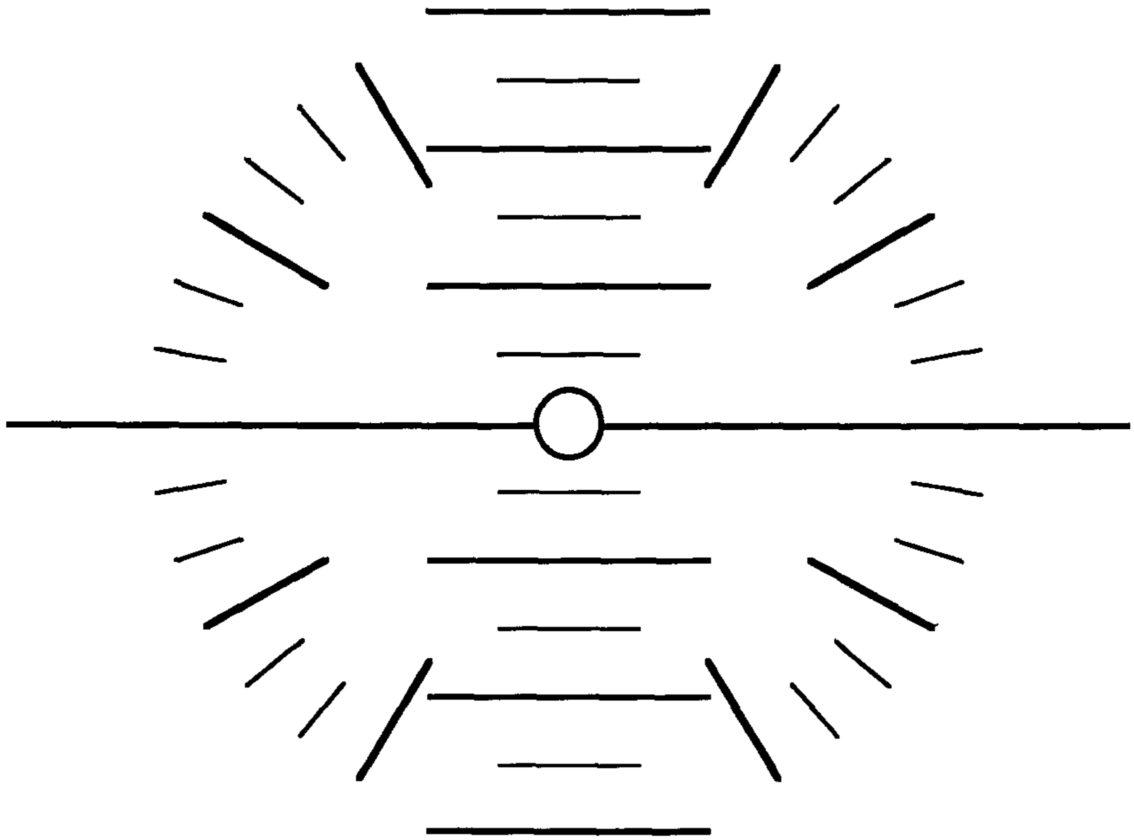


Figure 2
VIDEO OVERLAY

Table I

BQM-147 FLYING QUALITIES AND PERFORMANCE
TEST CONFIGURATIONS

Configuration	Pilot Mode	Landing Gear	Throttle	Autopilot Mode
Catapult Takeoff (CTO)	External	Dolly	Max	Disengaged
Power (P)	External/Internal	Skids	Max	Disengaged
Cruise (CR)(1)	External/Internal	Skids	Max Range Power	Disengaged
Landing (L)	External	Skids	Idle Cutoff	Disengaged
Autopilot Cruise (Auto CR)(2)	Internal	Skids	Max Range Power	RC link with wing leveling

NOTES: (1) Lower antenna retracted or extended.
(2) Lower antenna extended. All others had lower antenna retracted.

Table II

BQM-147 FLYING QUALITIES AND PERFORMANCE
FLIGHT TEST ACCOMPLISHMENT MATRIX

Event	Maneuver	Configuration	Altitude (ft MSL)	Remarks
1	Takeoff	CTO	SURF - 25	Assessed takeoff performance and controllability.
2	Climb	P	25 - 500	Assessed controllability.
3	Static Stability	CR	1,000 - 1,200	Suppressed phugoid and stabilized at trim RPM. Moved longitudinal stick and allowed to stabilize. Recorded new RPM.
4	Pitch Frequency Sweep	CR, P	1,000 - 1,200	Started slow and increased frequency until maximum amplitude observed on video pitch reference.
5	Pitch Doublet	CR, P	1,000 - 1,200	Executed at damped ω_{sp}. Counted overshoots in θ on video pitch reference.
6	Phugoid	CR, P	1,000 - 1,200	Slowed to one large bar noseup on the video overlay and released. Recorded times at $\theta = 0$. Noted θ peaks on video pitch reference.
7	Yaw Frequency Sweep	CR, P	1,000 - 1,200	Started slow and increased frequency until maximum amplitude observed on video yaw reference.
8	Rudder Doublet	CR, P, Auto CR	1,000 - 1,200	Executed at damped ω_d. Counted overshoots in ψ on video yaw reference.
9	Bank-to-Bank Rolls	CR	1,000 - 1,200	Initiated 1/4 to 1/2 stick roll at 20 deg ϕ, neutralized controls at 0 deg ϕ, and timed to 0 roll rate.
10	Aileron Turns Only	CR, P, Auto CR	1,000 - 1,200	Data taken during entry, steady turn, and exit. Did left and right turns stabilized at 20, 45, and 60 deg angle of bank. HQR's TASK: Bank angle capture, and small bank angle changes. Tolerance Desired: ±2 deg Acceptable: ±5 deg Task: Heading capture Tolerance Desired: ±2 deg Acceptable ±5 deg

Table II (Cont'd)

Event	Maneuver	Configuration	Altitude (ft MSL)	Remarks
11	Rudder Only Turns	CR, P	1,000 - 1,200	Data taken during entry, steady turn, and exit. Did left and right. HQR's TASK: Bank angle capture, and small bank angle changes. Tolerance Desired: ±2 deg Acceptable: ±5 deg Task: Heading capture Tolerance Desired: ±2 deg Acceptable: ±5 deg
12	Flat Turns	CR	1,000 - 1,200	Attempted left and right 360 deg turns. Task: Maintain 0 deg bank angle. Tolerance Desired: ±2 deg Acceptable ±5 deg Task: Heading capture Tolerance Desired: ±2 deg Acceptable: ±5 deg
13	Spiral Stability	CR, P, Auto CR	1,000 - 1,200	Started in 20 deg bank, released controls and recorded time to half or double amplitude. Checked for proper aileron centering by releasing controls into and away from turn. Did left and right.
14	Steady Heading Sideslip	CR, P	1,000 - 1,200	Used 1/4, 1/2, and full rudder deflection. Did left and right.
15	Landing	L	500 - SURF	Recorded pilot comments for normal landing.
16	1-g Stalls	NA	NA	Not accomplished due to early termination of test.
17	Accel. Stalls	NA	NA	Not accomplished due to early termination of test.
18	Maximum Flight Level Speed	NA	NA	Not accomplished due to early termination of test.

Table III

MISSION TASK DATA FROM
AILERON-ONLY AND RUDDER-ONLY TURNS

Power Setting	Antenna Position	Maneuver	Task	HQR Left Turn	HQR Right Turn
6,000 RPM	Retracted	A O Turn(1)	AOB(3)	3	3
6,000 RPM	Retracted	R O Turn(2)	AOB	3	3
6,000 RPM	Extended	A O Turn	AOB	2	2
6,000 RPM	Extended	R O Turn	AOB	3	3
MAX	Retracted	A O Turn	AOB	3	3
MAX	Retracted	R O Turn	AOB	2	3
6,000 RPM	Retracted	A O Turn	HDG(4)	6	5
6,000 RPM	Retracted	R O Turn	HDG	5	5
6,000 RPM	Extended	A O Turn	HDG	5	5
6,000 RPM	Extended	R O Turn	HDG	5	4
MAX	Retracted	A O Turn	HDG	4	4
MAX	Retracted	R O Turn	HDG	4	4

NOTES:
(1) Aileron only turn.
(2) Rudder only turn.
(3) 20 deg and 45 deg angle-of-bank capture.
(4) Heading capture.

Annex E – AGARD and RTO
Flight Test Instrumentation and Flight Test Techniques Series

1. Volumes in the AGARD and RTO Flight Test Instrumentation Series, AGARDograph 160

Volume Number	Title	Publication Date
1.	Basic Principles of Flight Test Instrumentation Engineering (Issue 2)	
	Issue 1: Edited by A. Pool and D. Bosman	1974
	Issue 2: Edited by R. Borek and A. Pool	1994
2.	In-Flight Temperature Measurements by F. Trenkle and M. Reinhardt	1973
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17.	Analogue Signal Conditioning for Flight Test Instrumentation by D.W. Veatch and R.K. Bogue	1986
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21.	Differential Global Positioning System (DGPS) for Flight Testing by R. Sabatini and G.B. Palmerini	2008

2. Volumes in the AGARD and RTO Flight Test Techniques Series

Volume Number	Title	Publication Date
AG237	Guide to In-Flight Thrust Measurement of Turbojets and Fan Engines by the MIDAP Study Group (UK)	1979

The remaining volumes are published as a sequence of Volume Numbers of AGARDograph 300.

Volume Number	Title	Publication Date
1.	Calibration of Air-Data Systems and Flow Direction Sensors by J.A. Lawford and K.R. Nippress	1988
2.	Identification of Dynamic Systems by R.E. Maine and K.W. Iliff	1988
3.	Identification of Dynamic Systems – Applications to Aircraft Part 1: The Output Error Approach by R.E. Maine and K.W. Iliff Part 2: Nonlinear Analysis and Manoeuvre Design by J.A. Mulder, J.K. Sridhar and J.H. Breeman	 1986 1994
4.	Determination of Antenna Patterns and Radar Reflection Characteristics of Aircraft by H. Bothe and D. McDonald	1986
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27.	Unique Aspects of Flight Testing Unmanned Aircraft Systems by A.E. Pontzer, M.D. Lower and J.R. Miller	2010

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Aircraft Electronic Warfare Test and Evaluation

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14. Abstract

Unmanned Aircraft Systems (UASs) must be flight tested in order to be effectively and safely used in operational scenarios. This AGARDograph documents both classic air vehicle flight test techniques and considerations developed from manned flight testing along with special flight test and risk management considerations devised specifically for UAS testing to establish a baseline for conducting flight testing of unmanned systems. Air vehicles ranging in size from small vehicles to high altitude, long endurance aircraft are covered along with flight termination systems, data link considerations, and implications of test locations. Emphasis is placed on evaluating not only the air vehicle but the airborne systems and sensors which make up a UAS payload and the choice of instrumentation systems needed to establish system performance. Even considering the continuous development of new test techniques driven by the rapid growth of unmanned systems and expansion of these systems' capabilities, this document should aide in establishing a suitable baseline for UAS flight testing.

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